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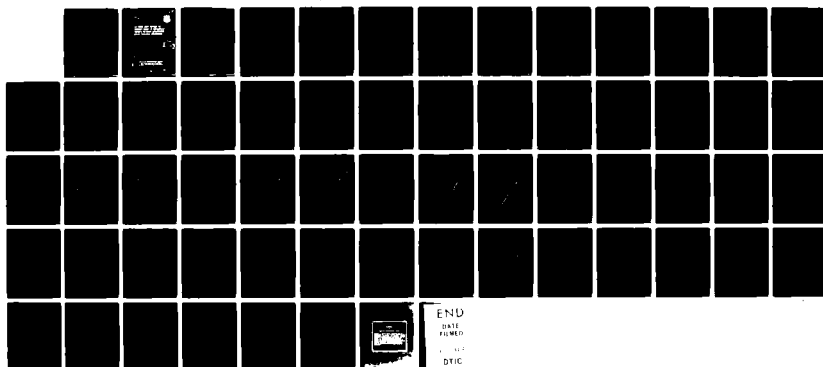
SCATTERING CROSS SECTIONS FOR COMPOSITE MODELS OF  
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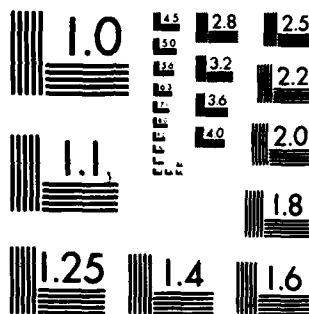
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# SCATTERING CROSS SECTIONS FOR COMPOSITE MODELS OF NON-ABSORBING SURFACES FOR WHICH DECORRELATION IMPLIES STATISTICAL INDEPENDENCE

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APPROVED FOR PUBLICATION

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number) The full wave approach is used to determine the scattering cross sections for composite models of non-Gaussian rough surfaces. It is assumed in this work that the rough surface heights become statistically independent when they decorrelate, thus no delta function type specular term appears in the expression for the scattered fields. The broad family of non-Gaussian surfaces considered range in the limit from exponential to Gaussian. It is seen that for small angles of incidence, the like (over)		

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polarized cross sections have the same dependence on the special form of the surface height joint probability density, but for large angles the scattering cross sections for the horizontally polarized waves are much more sensitive to the special form of the joint probability density. The corresponding results for the depolarized backscatter cross section are also presented. The shadow functions are shown to be rather insensitive to the special form of the joint probability density.



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## 1. Introduction

In this work the full wave approach is used to determine the scattering cross sections for composite models of non-Gaussian rough surfaces. In particular, it is assumed here that the rough surface is characterized by a family of joint height probability densities that have been developed by Beckmann (1973a,b) for non-Gaussian surfaces. These joint height probability densities are expressed as an infinite sum of powers of the correlation coefficient and it is assumed that decorrelation of surface heights implies statistical independence. Using these joint probability density functions, Beckmann (1973a,b) derives physical optics and geometrical optics approximations for the scattering cross sections. Recently, Brown considered rough surfaces with exponential joint height probability densities (Brown, 1982). In his work Brown concludes that the appearance of a delta function type specular term in his results "suggests that decorrelation does indeed imply statistical independence for real surfaces."

In Section 2 the principal elements of the full wave approach are summarized. In Sections 3 and 4, the expressions for the marginal slope densities and the shadow functions for the non-Gaussian surfaces are derived. In Section 5 illustrative examples are presented. By considering a very broad family of non-Gaussian rough surfaces that include in the limits the exponential and the Gaussian surfaces, it is possible to derive the full wave solutions for the backscatter cross sections for more realistic models of rough surfaces. Since it is assumed in this work that decorrelation of the surface heights implies statistical

independence, no delta function type specular terms are obtained in these results. It is found that for angles of incidence  $\theta_0^1 > 25^\circ$ , the backscatter cross section for the horizontally polarized waves are more sensitive to the specific form of the joint height probability density assumed. The reason for this is given in Section 5. For near normal incidence both the backscatter cross sections for vertically and horizontally polarized waves, exhibit the same dependence on the special form of the joint height probability density assumed. The depolarized backscatter cross sections are sensitive to the special form of the surface statistics only near normal incidence.

It is interesting to note that for the mean square slopes considered in the illustrative examples, the shadow functions for the non-Gaussian surfaces are practically indistinguishable from the shadow function for the Gaussian surface, nevertheless the backscatter cross sections are sensitive to the precise form of the surface height statistics assumed (see Section 5).



## 2. Formulation of the Problem

The full wave solutions for the scattering cross sections are summarized in this section for a two scale model of random rough surfaces  $h(x,z)$  (See Fig. 1) (Bahar et al 1982). To this end consider the Fourier transform of the surface height autocorrelation function  $\langle h(x,z)h'(x',z') \rangle$  which is the surface height spectral density function (Rice 1951)

$$W(v_x, v_z) = \frac{1}{\pi^2} \int_{-\infty}^{\infty} \exp(i v_x x_d + i v_z z_d) \langle h(x,z)h'(x',z') \rangle dx_d dz_d \quad (2.1)$$

In (2.1) the symbol  $\langle \rangle$  denotes statistical average and

$$\bar{v} = k_0 (\bar{n}^f - \bar{n}^i) = v_x \bar{a}_x + v_y \bar{a}_y + v_z \bar{a}_z, \quad |\bar{v}| = v \quad (2.2a)$$

in which  $\bar{n}^i$  and  $\bar{n}^f$  are unit vectors in the directions of the incident and scattered waves

$$\bar{n}^i = \sin \theta_0^i \cos \phi^i \bar{a}_x - \cos \theta_0^i \bar{a}_y + \sin \theta_0^i \sin \phi^i \bar{a}_z = \bar{k}^i / k_0 \quad (2.2b)$$

$$\bar{n}^f = \sin \theta_0^f \cos \phi^f \bar{a}_x + \cos \theta_0^f \bar{a}_y + \sin \theta_0^f \sin \phi^f \bar{a}_z = \bar{k}^f / k_0 \quad (2.2c)$$

and  $k_0 = \omega(\epsilon_0 \mu_0)^{1/2}$  is the free space wavenumber characterized by the permittivity  $\epsilon_0$  and permeability  $\mu_0$ . An  $\exp(i\omega t)$  time dependence is assumed in this work.

The distance between two points in the reference  $(x,z)$  plane is

$$r_d = |\bar{r}_d| = |x_d \bar{a}_x + z_d \bar{a}_z| = |(x-x')\bar{a}_x + (z-z')\bar{a}_z| \quad (2.3)$$

For convenience the rough surface height  $h(x,z)$  is decomposed into two parts

$$h(x,z) = h_\ell(x,z) + h_s(x,z) \quad (2.4)$$

the first term  $h_\ell$  consists of the large scale spectral components

$$0 \leq k^2 \equiv v_x^2 + v_z^2 \leq k_d^2 \quad (2.5)$$

where  $k_d$  is the wavenumber where spectral splitting is assumed to occur (Brown 1978, 1980). In this work the wavenumber  $k_d$  is chosen such that

the surface  $h_\ell$  meets the radii of curvature criteria (associated with the Kirchhoff approximations for the surface fields). It is also assumed here that the surface  $h_\ell$  meets the condition for deep phase modulation (Bahar et al 1982). The second term in (2.4),  $h_g$ , consists of the small scale spectral components

$$k_d < k \leq k_c \quad (2.6)$$

where  $k_c$  is the spectral cutoff wavenumber (Brown 1978). The full wave scattering cross section for the composite surface (2.4) which accounts for both specular scatter and Bragg scatter in a self-consistent manner is given by the weighted sum of two cross sections (Bahar et al 1982)

$$\langle \sigma^{PQ} \rangle_T = \langle \sigma^{PQ} \rangle_O + \langle \sigma^{PQ} \rangle_R \quad (2.7)$$

in which the first and second superscripts (P and Q, V for vertical, H for horizontal) denote the polarization of the scattered and incident waves respectively. The first term in (2.7) is the scattering cross section associated with the surface  $h_\ell$ . Thus

$$\langle \sigma^{PQ} \rangle_O = |\chi^s(v)|^2 \langle \sigma_\infty^{PQ} \rangle \quad (2.8)$$

where

$$\langle \sigma_\infty^{PQ} \rangle = \frac{4\pi k_o^2}{v_y^2} \left[ \left| \frac{D^{PQ}}{\bar{n} \cdot \bar{a}_y} \right|^2 P_2(\bar{n}^f, \bar{n}^i | \bar{n}) P(\bar{n}) \right]_{\bar{n} \rightarrow \bar{n}_s} \quad (2.9)$$

In (2.8) the characteristic function for the surface  $h_g$ ,  $\chi^s(v)$ , has the effect of decreasing the contribution of the physical optics scattering cross section  $\langle \sigma_\infty^{PQ} \rangle$ . As  $\langle h_g^2 \rangle$ , the mean square of the small scale surface height (that rides on the large scale surface  $h_\ell$ ), approaches zero,  $|\chi^s|^2 \rightarrow 1$ . It is assumed in this work that the small scale surface height,  $h_g$ , has a Gaussian distribution and in this case the coefficient  $|\chi^s|^2$  in (2.8) is

$$|\chi^s(v)|^2 = |\langle \exp i v h_s \rangle|^2 = \exp(-4k_0^2 \langle h_s^2 \rangle) = \exp(-\beta) \quad (2.10)$$

Thus the effective weighting function,  $|\chi^s|^2$ , decreases monotonically as  $\beta = 4k_0^2 \langle h_s^2 \rangle$  increases. The shadow function  $P_2(\bar{n}^f, \bar{n}^i | \bar{n})$  is the probability that a point on the rough surface is both illuminated by the source and visible at the observation point given the value of the slopes  $h_x, h_z$  at that point (Smith 1967, Sancer 1969). The unit vector normal to the rough surface is

$$\begin{aligned} \bar{n} &= \nabla(y - h_\ell(x, z)) / |\nabla(y - h_\ell(x, z))| \approx \nabla(y - h(x, z)) / |\nabla(y - h(x, z))| \\ &= (-h_x \bar{a}_x + \bar{a}_y - h_z \bar{a}_z) / (h_x^2 + 1 + h_z^2)^{1/2} \end{aligned} \quad (2.11a)$$

where

$$h_x = \partial h / \partial x, \quad h_z = \partial h / \partial z \quad (2.11b)$$

and

$$\bar{n}_s = \bar{v} / v \quad (2.11c)$$

is the value of  $\bar{n}$  at the specular points of the rough surface. Furthermore,  $p(\bar{n}) = p(h_x, h_z)$  is the joint probability density function for the slopes of the large scale surface  $h_\ell$ . In this work the joint probability density function for the large scale surface height  $h_\ell(x, z)$  and its associated slope distribution function are assumed to be either Gaussian or non-Gaussian (Beckmann 1973a, b, see Section 3).

The coefficient  $D^{PQ}$  in (2.9) depends on the polarization of the scattered and incident waves, the unit vectors  $\bar{n}^i, \bar{n}^f$  and  $\bar{n}$  and the permittivity  $\epsilon$  and permeability  $\mu$  of the media above and below the rough surface  $h(x, z)$  (Bahar 1981a, b).

The second term in (2.7) is the scattering cross section associated with the small scale surface  $h_s$  (that rides on the large scale surface).

Thus (Bahar et al, 1982)

$$\langle \sigma^{PQ} \rangle_R = 4k_0^2 \sum_{m=1}^{\infty} \int \frac{|D^{PQ} \chi^s(\vec{v}_{\bar{y}})|^2}{\bar{n} \cdot \bar{a}_y} \left( \frac{\vec{v}_{\bar{y}}}{2} \right)^{2m} \frac{W_m(\vec{v}_{\bar{x}}, \vec{v}_{\bar{z}})}{m!} \quad (2.13)$$

$$\cdot P_2(\bar{n}^{-f}, \bar{n}^{-1} | \bar{n}) p(n) dh_x dh_z = \sum_{m=1}^{\infty} \langle \sigma^{PQ} \rangle_{Rm} \quad (2.13)$$

In (2.13)  $W_m$  is the two dimensional Fourier transform

$$\begin{aligned} \frac{W_m(\vec{v}_{\bar{x}}, \vec{v}_{\bar{z}})}{2^{2m}} &= \frac{1}{2\pi^2} \int \langle h_1 h_1' \rangle^m \exp(i\vec{v}_{\bar{x}} \bar{x}_d + i\vec{v}_{\bar{z}} \bar{z}_d) d\bar{x}_d d\bar{z}_d \\ &= \frac{1}{2^{2m}} \int W_{m-1}(\vec{v}_{\bar{x}}', \vec{v}_{\bar{z}}') W_1(\vec{v}_{\bar{x}} - \vec{v}_{\bar{x}}', \vec{v}_{\bar{z}} - \vec{v}_{\bar{z}}') d\vec{v}_{\bar{x}}' d\vec{v}_{\bar{z}}' \\ &= \frac{1}{2^{2m}} W_{m-1}(\vec{v}_{\bar{x}}, \vec{v}_{\bar{z}}) \otimes W_1(\vec{v}_{\bar{x}}, \vec{v}_{\bar{z}}) \end{aligned} \quad (2.14)$$

where the symbol  $\otimes$  denotes the two dimensional convolution of  $W_{m-1}$  with  $W_1$ , the surface height spectral density function for the small scale surface  $h_s$ . Thus

$$W_1(\vec{v}_{\bar{x}}, \vec{v}_{\bar{z}}) = \begin{cases} W(\vec{v}_{\bar{x}}, \vec{v}_{\bar{z}}) & \text{for } k > k_d \\ 0 & \text{for } k \leq k_d \end{cases} \quad (2.15)$$

and  $\vec{v}_{\bar{x}}$  and  $\vec{v}_{\bar{z}}$  are the orthogonal components of the vector  $\vec{v}$  (2.2) tangent to the surface  $h_\ell(x, z)$  while  $\vec{v}_y$  is the component of  $\vec{v}$  normal to the surface  $h_\ell$ . Thus  $\vec{v}$  in the local coordinate system associated with the rough surface  $h_\ell$  can be expressed as (see Fig. 2)

$$\vec{v} = v_x \bar{n}_1 + v_y \bar{n}_2 + v_z \bar{n}_3 \quad (2.16a)$$

where

$$\bar{n}_1 = (\bar{n} \times \bar{a}_z) / |\bar{n} \times \bar{a}_z|, \bar{n}_2 = \bar{n}, \bar{n}_3 = \bar{n}_1 \times \bar{n} \quad (2.16b)$$

and

$$v_{\bar{x}} = \vec{v} \cdot \bar{n}_1, v_{\bar{y}} = \vec{v} \cdot \bar{n}_2, v_{\bar{z}} = \vec{v} \cdot \bar{n}_3 \quad (2.16c)$$

Using the full wave approach it is shown that a suitable value for  $k_d$  (the wavenumber where spectral splitting is assumed to occur) is obtained by setting  $\beta = 4k_0^2 \langle h_s^2 \rangle = 1.0$  since for this value of  $\beta$  the assumed condition for deep phase modulation is satisfied. For  $\beta \geq 1.0$  the total scattering cross section (2.7) is insensitive to variations in the value of  $k_d$  (Bahar et al 1982). However, since  $k_d$  decreases as  $\beta$  increases, it is necessary to evaluate more terms in (2.13) for larger values of  $\beta$ .

### 3. Non-Gaussian Joint Probability Density Functions for the Large Scale Surface Heights and the Associated Slope Distribution Function

The principal purpose of this work is to apply the full wave approach to scattering from rough surfaces to surfaces with non-Gaussian surface height distribution functions and to compare the results with these for Gaussian surfaces. In his recent work, Brown (1982) investigates scattering by surfaces for which decorrelation does not imply statistical independence. In this work Brown concludes that the appearance of a specular term coupled with the lack of any experimental scattering data supporting this result "suggests that decorrelation does indeed imply statistical independence for real surfaces."

Thus, even though from a mathematical point of view, statistical independence is not, in general, implied by a lack of correlation (Papoulis 1965), it is assumed in this work that the joint surface height distribution function becomes statistically independent as the surface height decorrelates. Beckmann (1973a,b) derives a method for finding the joint distribution function for the surface height,  $f(h, h'; r_d)$ , from a given marginal  $p(h)$  that is not necessarily normal and a given correlation coefficient  $R(r_d)$ .

Thus following Beckmann<sup>†</sup> (1973a,b)  $f(h,h';r_d)$  is expressed as follows

$$f(h,h';r_d) = p(h)p(h') \sum_{n=0}^{\infty} \frac{R_n^2(r_d)}{q_n} Q_n(h)Q_n(h') \quad (3.1)$$

where the identical functions  $p(h)$  and  $p(h')$  are the marginals satisfying

$$\int f(h,h';r_d)dh' = p(h) , \quad \int f(h,h';r_d)dh = p(h') \quad (3.2)$$

From (3.2) it also follows that

$$\int \int f(h,h';r_d)dhdh' = 1 \quad (3.3)$$

In (3.1) it is assumed that the given surface height density function is transformed into a density  $p(h)$  which is proportional to the weighting function of a classical set of orthogonal polynomials  $Q_n(h)$ , i.e.,

$$\int p(h)Q_n(h)Q_m(h)dh = \begin{cases} 0 & n \neq m \\ \frac{2}{q_n} & n=m \end{cases} \quad (3.4)$$

where all  $q_n$  are positive and

$$Q_0 = 1 \quad (3.5)$$

thus  $q_0 = 1$ . Beckmann (1973a) shows that

$$f(h,h';r_d) = \sum_{n=0}^{\infty} \frac{R_n^2(r_d)}{q_n} Q_n(h)Q_n(h') \geq 0 \quad (3.6)$$

thus

$$f(h,h';r_d) \geq 0 \quad (3.7)$$

throughout the domain  $a \leq h,h' \leq b$  (where the orthogonality interval of the polynomials  $Q_n$  is  $a,b$  (3.4)). Furthermore, it can be shown that

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<sup>†</sup>For the convenience of the reader, Beckmann's principal results are summarized here. Since there are several errors in the published results, corrected equations are denoted here by the symbol \* next to the equation number.

$$\begin{aligned}
\langle hh' \rangle &= \iint hh' f(h, h'; r_d) dh dh' = \sum_{n=0}^{\infty} \frac{R^n(r_d)}{q_n^2} \left[ \int hp(h) Q_n(h) dh \right]^2 \\
&= R(r_d) (\langle h^2 \rangle - \langle h \rangle^2) + \langle h \rangle^2
\end{aligned} \tag{3.8}$$

in agreement with the condition  $f(h, h'; r_d)$  must fulfill if it is to be a two dimensional density of a random process with given correlation coefficient  $R(r_d)$ . In addition (3.1) clearly satisfies

$$\lim_{r_d \rightarrow \infty} f(h, h'; r_d) \rightarrow p(h)p(h') \tag{3.9}$$

Finally express the function  $g(h)$  as follows in an infinite series of orthogonal polynomials

$$g(h) = \sum_{n=0}^{\infty} \alpha_n Q_n(h) \tag{3.10}$$

where on using (3.4) the constant  $\alpha_n$  is

$$\alpha_n = \int g(h') p(h') Q_n(h') dh' / q_n^2 \tag{3.11}$$

On interchanging integration on summation (3.10) can be written as

$$g(h) = \int g(h') [p(h') \sum_{n=0}^{\infty} \frac{1}{q_n^2} Q_n(h) Q_n(h')] dh' \tag{3.12}$$

thus the quantity in square brackets is the Dirac delta function  $\delta(h-h')$ .

Thus from (3.1) it follows that

$$\lim_{r_d \rightarrow 0} f(h, h'; r_d) = p(h)\delta(h-h') = p(h')\delta(h-h') \tag{*3.13}$$

On integrating (3.13) with respect to  $h$  and  $h'$  it is readily shown to satisfy (3.3). (Contrary to the statements by Beckmann (1973a,b), the Dirac delta function does not remain unchanged when multiplied by  $p(h)$  and  $\lim_{r_d \rightarrow 0} f(h, h'; r_d) \neq \delta(h-h')$ ). In Beckmann's work (1973a,b), the orthogonal polynomials  $Q_n(h)$  can be the Hermite polynomials, the generalized Laguerre polynomials or the

Jacobi polynomials. However, in this work it is assumed for convenience that  $Q_n$  are the generalized Laguerre polynomials (Abramowitz and Stegun (1964))

$$Q_n(h) = L_n^{(k-1)}(h) \quad (3.14)$$

Since the weighting functions associated with the Laguerre polynomials are proportional to the gamma functions, the marginals for the large scale surface height probability density functions are the gamma distributions

$$p(h) = \frac{v^k h^{k-1} e^{-vh}}{(k-1)!}, \quad h \geq 0 \quad (3.15)$$

for which the mean is  $\langle h \rangle = k/v$ , the variance is  $\sigma^2 = k/v^2$  and the normalization constant  $q_n^2$  (3.4) is

$$q_n^2 = (k + n-1)! / (k-1)! n! \quad *(3.16)$$

For  $k = 1$  (3.15) reduces to the exponential distribution

$$p(h) = v e^{-vh}, \quad (k=1) \quad (3.17)$$

and for the limiting case  $k \rightarrow \infty$  (3.15) reduces to the Gaussian distribution by virtue of the Central Limit Theorem. (For most practical purposes  $k \geq 25$  is sufficiently close to the limiting case).

$$p(h) = \frac{1}{\sigma\sqrt{2\pi}} \exp \left[ -\frac{(h-\langle h \rangle)^2}{2\sigma^2} \right], \quad (k \rightarrow \infty) \quad (3.18)$$

where  $\sigma^2$  is the variance and  $\langle h \rangle$  is the mean height.

Thus using the gamma distribution (3.15), it is sufficient to vary one parameter  $k$  to examine the effects of changing the marginal height distribution from exponential to normal in gradual steps.

Following the procedures outlined above, the joint distribution for the surface heights whose marginals are  $p(h)$  (3.15) (with  $v = 1$  and variance  $k$  can be shown to be given by (Beckmann 1973b))



$$f(h, h'; r_d) = \frac{(hh')^{k-1} e^{-(h+h')}}{[(k-1)!]} \sum_{n=0}^{\infty} \frac{R^n(r_d)n!}{(k+n-1)!} L_n^{k-1}(h) L_n^{k-1}(h') \quad (3.19)$$

in which  $L_n^{k-1}(h)$  are Laguerre orthogonal polynomials (Abramowitz and Stegun 1964). The corresponding (one dimensional) slope distribution function  $p(h_x)$  can be obtained from the inverse Fourier transform

$$p(h_x) = \lim_{r_d \rightarrow 0} \frac{r_d}{2} \int \sum_{n=0}^{\infty} \frac{R^n(r_d)}{q_n^2} \int p(h) L_n^{k-1}(h) \exp(iwh) |^2 \exp(-ir_d h_x w) dw \quad (3.20)$$

where

$$\begin{aligned} \sum_{n=0}^{\infty} \frac{R^n}{q_n^2} \left| \int p(h) L_n^{k-1}(h) \exp(iwh) dh \right|^2 &= \sum_{n=0}^{\infty} \frac{(n+k-1)! w^{2n} R^n}{n! (1+w^2)^{k+n} (k-1)!} \\ &= \frac{1}{[1 + (1-R)w^2]^k} \end{aligned} \quad *(3.21)$$

Thus

$$p(h_x) = \lim_{r_d \rightarrow 0} \frac{r_d}{2\pi} \int_{-\infty}^{\infty} \frac{\exp(-iwh_x) dw}{(1 + w^2/w_0^2)^k} \quad (3.22a)$$

where the  $k^{th}$  order poles are at points

$$w_{\pm} = \pm i/\sqrt{1-R} = \pm i w_0 \quad (3.22b)$$

Using standard procedures for integration in the complex  $w$  plane, the path along the real axis is closed by an infinite semicircle in the lower or upper half plane depending on whether  $z > 0$  or  $z < 0$ . Thus the pole enclosed by the contour is at

$$w = \begin{cases} w_- = -i w_0, & \text{for } z > 0 \\ w_+ = i w_0, & \text{for } z < 0 \end{cases} \quad *(3.23)$$

and (3.22) reduces to

$$p(h_x) = \frac{y e^{-\gamma |h_x|}}{2^{2k-1} (k-1)!} \sum_{j=0}^{k-1} \frac{(2k-j-2)! (2\gamma |h_x|)^j}{j! (k-j-1)!} \quad *(3.24)$$

where

$$\gamma = \lim_{r_d \rightarrow 0} r_d w_0 = \lim_{r_d \rightarrow 0} r_d / \sqrt{1-R} \quad (3.25)$$

For a stationary random process, the correlation function is an even function of  $r_d$  (Beckmann 1968) and for small  $r_d$

$$R(r_d) = 1 - \frac{\sigma_x^2}{2\sigma^2} r_d^2 + O(r_d^4) \quad (3.26)$$

where  $\sigma_x^2$  is the mean square slope

$$\sigma_x^2 = -\sigma^2 R''(0) \quad (3.27)$$

Therefore (3.25) reduces to

$$\gamma = \frac{\sqrt{2} \sigma}{\sigma_x} = \frac{\sqrt{2k}}{\sigma_x}, \quad (v=1) \quad *(3.28)$$

and the slope distribution function corresponding to the two dimensional gamma (surface height) distribution (3.19) is

$$p(h_x) = \frac{2\sqrt{2k} \exp(-\sqrt{2k} |h_x| / \sigma_x)}{\sigma_x 2^{2k} (k-1)!} \sum_{j=0}^{k-1} \frac{(2k-j-2)!}{j! (k-j-1)!} (2\sqrt{2k} |h_x| / \sigma_x)^j \quad *(3.29)$$

The above result can be shown to hold for arbitrary values of  $v$  and not just  $v = 1$  (Beckmann 1973a). It is assumed in this work that the probability density for the slopes  $h_x$  and  $h_z$  are independent (as for the Gaussian case Barrick 1970, Brown 1978, Bahar 1981a,b), thus the two dimensional slope distribution for the large scale surface is

$$p(\vec{n}) = p(h_x, h_z) = p(h_x) p(h_z) \quad (3.30)$$

in which  $p(h_x)$  and  $p(h_z)$  are the same functions as in (3.29). The corresponding slope distribution function is

$$p(h_x) = \frac{1}{\sqrt{2\pi} \sigma_x} \exp(-h_x^2 / 2\sigma_x^2) \quad (3.31)$$

#### 4. The Explicit Expression for the Shadow Functions Associated with the Non-Gaussian Surface Height Distribution Functions

In this section explicit expressions are derived for the shadow functions related to the non-Gaussian surface height distribution functions considered in Section 3. Brown (1980) recently developed a very convenient procedure to evaluate the shadow functions for surfaces with non-Gaussian height distribution. Following Smith's work (1967), Brown (1980) assumes that the surface heights  $h$  and slopes  $h_x$  at points separated by the distance  $r_d$  are uncorrelated. In addition Brown assumes that decorrelation implies statistical independence. Thus keeping the notation used in this paper, the shadow function for backscatter ( $\bar{n}^i = -\bar{n}^1$ ),  $P_2(-\bar{n}^1, \bar{n}^1 | \bar{n})$ , is the probability that a point on the rough surface is illuminated by the source (and visible at the observation point) given the value of the slope at that point.

$$P_2(-\bar{n}^1, \bar{n}^1 | \bar{n}) = S(-\bar{n}^1 \cdot \bar{n}) / [1 + \Gamma^1 / \mu^1] \quad (4.1)$$

where  $S(-\bar{n}^1 \cdot \bar{n})$  is the unit step function. The argument  $-\bar{n}^1 \cdot \bar{n}$  vanishes when the incident (or backscattered) wave normal is tangent to the surface.

Thus, when the plane of incidence is the  $x, y$  plane (see Fig. 1), the argument  $(-\bar{n}^1 \cdot \bar{n})$  vanishes for

$$\mu^1 \equiv \cot \theta_o^1 = \partial h / \partial x \equiv h_x \quad (4.2)$$

in which  $\theta_o^1$  is the angle of incidence (2.26) with respect to the reference surface (the  $x, z$  plane). Furthermore, in (4.1)

$$\Gamma^1 \equiv \Gamma(\mu^1) = \int_{\mu^1}^{\infty} (h_x - \mu^1) p(h_x) dh_x \quad (4.3)$$

in which  $p(h_x)$  is the one dimensional slope distribution function. On substituting the non-Gaussian slope distribution function (3.29) (associated

with the gamma surface height distribution) it can be shown that

$$\Gamma(\mu^i)/\mu^i = \frac{\exp(-\sqrt{2k} \mu/\sigma_x)}{2^{2k-1} (k-1)!} \sum_{j=0}^{k-1} \frac{(2k-j-2)!}{(k-j-1)!} 2^j \sum_{r=1}^{j+1} \frac{r(\sqrt{2k} \mu/\sigma_x)^{j-r}}{(j+1-r)!} \quad (4.4)$$

The shadow function for the bistatic case,  $\bar{n}^f \neq -\bar{n}^i$ , is (Brown 1980)

$$P_2(\bar{n}^f, \bar{n}^i | \bar{n}) = \begin{cases} \frac{S(-\bar{n}^i \cdot \bar{n})}{1 + \Gamma^i/\mu^i} & , \theta_o^i \geq \theta_o^f, \phi^f - \phi^i = \pi \\ \frac{S(\bar{n}^f \cdot \bar{n})}{1 + \Gamma^f/\mu^f} & , \theta_o^f \geq \theta_o^i, \phi^f - \phi^i = \pi \\ \frac{S(\bar{n}^f \cdot \bar{n})S(-\bar{n}^i \cdot \bar{n})}{1 + (\Gamma^i/\mu^i) + (\Gamma^f/\mu^f)} & , \text{ elsewhere} \end{cases} \quad (4.5)$$

In (4.5)

$$\Gamma^f = \Gamma(\mu^f) \text{ and } \mu^f = \cot \theta_o^f \quad (4.6)$$

where  $\theta_o^f$  is the scatter angle (2.2c) with respect to the reference plane.

The above expressions (4.5) are also in agreement with Sancer's (1969) results for Gaussian surface height distributions. (In Sancer's published results (1969), the inequality symbols should be reversed, Brown (1980)).

## 5. Illustrative Examples

In this section the like and depolarized backscatter cross sections are evaluated for several composite models of perfectly conducting rough surfaces with different surface height distribution functions. The surface  $h_L$  consisting of the large scale spectral components,  $0 \leq k \leq k_d$ , is assumed to be characterized by the gamma surface height distribution function (3.15) and the associated non-Gaussian slope distribution function (3.29). For the illustrative examples presented here the parameter  $k$  is set equal to 1, 2, 5 and 25 and the limiting case ( $k \rightarrow \infty$ ) is represented by the Gaussian distribution (3.18). Two different total mean square slopes are considered

(a)  $\sigma_{lt}^2 = 0.0171$  and (b)  $\sigma_{lt}^2 = 0.0564$ . The surface  $h_s$  consisting of the small scale spectral components,  $k \geq k_d$ , is characterized by Gaussian surface height distribution functions. The wavenumber  $k_d$  where spectral splitting is assumed to occur is determined by setting  $\beta = 4k_o^2 \langle h_s^2 \rangle = 1$  (Bahar et al 1982) and the specific form assumed for the surface height spectral density function (2.1) is (Brown 1978)

$$W(k) = \frac{\pi}{2} S(k) = \begin{cases} \frac{2}{\pi} B \frac{k^4}{(k^2 + \kappa^2)^4} & , k \leq k_c \\ 0 & , k > k_c \end{cases} \quad (5.1)$$

In (5.1)  $W(k)$  is the spectral density function employed by Rice (1951) and

$$\begin{aligned} B &= .0046 & (\text{case a}) & ; B = 0.0133 & (\text{case b}) \\ k^2 &= v_x^2 + v_z^2 & (\text{cm})^{-2} & ; k_c = 12 & (\text{cm})^{-1} \\ \kappa &= (335.2 V^4)^{-1/4} & (\text{cm})^{-1} & ; V = 4.3 & (\text{m/s}) \end{aligned} \quad (5.2)$$

The wavelength for the electromagnetic wave is

$$\lambda_o = 2 \text{ (cm)} , (k_o = 3.1416 \text{ (cm)}^{-1}) \quad (5.3)$$

The mean square height for the small scale surface  $h_s$  is

$$\langle h_s^2 \rangle = \int_0^{2\pi} \int_{k_d}^{k_c} \frac{W(k)}{4} k dk d\phi = \frac{B}{2} \left[ \frac{1}{k_d^2} - \frac{1}{k_c^2} \right] \quad (5.4)$$

and the total mean square slope for the large scale surface  $h_l$  is (Brown 1978)

$$\sigma_{lt}^2 = \sigma_x^2 + \sigma_z^2 = \int_0^\pi \int_0^{k_d} \frac{W(k)}{4} k^3 dk d\phi = \left[ -\frac{11}{16} + \ln \left[ \frac{k_d^2 + \kappa^2}{\kappa^2} \right] \right] \quad (5.5)$$

in which  $\sigma_x^2 = \sigma_z^2$ .

In Fig. 3,  $\sigma$  times the one dimensional gamma surface height distributions (3.15) are plotted as functions of  $h/\sigma$  for  $k = 1, 2, 5, 25$  together with the Gaussian surface height distribution (with  $\langle h \rangle / \sigma = \sqrt{k} = 5$ ). In Fig. 4, the corresponding one dimensional slope distributions times  $\sigma_{lt} = \sqrt{2} \sigma_{lx}$  are plotted as functions of  $h_x / \sigma_{lt}$ . In Fig. 5 the corresponding shadow functions (4.5) are plotted as functions of  $\theta_o^1$  for backscatter ( $\bar{n}^f = -\bar{n}^i$ ) (a)  $\sigma_{lt}^2 = 0.0171$ , (b)  $\sigma_{lt}^2 = 0.0564$ . As expected the shadow function is smaller for the larger mean slopes. The shadow functions are insensitive to the particular form of the slope density functions considered.

In Figs. 6a,b,c and 7a,b,c, the corresponding like polarized and depolarized total backscatter cross sections (2.7) are plotted as functions of  $\theta_o^1$  (a)  $\langle \sigma^{VV} \rangle$  (b)  $\langle \sigma^{HH} \rangle$  (c)  $\langle \sigma^{VH} \rangle = \langle \sigma^{HV} \rangle$  in Figs. 6a,b,c  $\sigma_{lt}^2 = 0.0171$  and in Figs. 7a,b,c  $\sigma_{lt}^2 = 0.0564$ . The like backscatter cross section near normal incidence ( $\theta_o \approx 0$ ) is largest for the case  $k = 1$ . This is expected since the case  $k = 1$  corresponds to a surface with a slope distribution which has the largest zero slope probability. On the other hand consistent with the above results, the depolarized backscatter cross sections near normal incidence are smallest for the case  $k = 1$ . The backscatter cross section for  $k = 25$  is practically indistinguishable from the backscatter for Gaussian random surfaces. Furthermore, as one may expect, the spread in the values for the backscatter cross sections as  $k$  varies from 1 through  $\infty$  increases as the mean square slope  $\sigma_{lt}^2$  increases. At large angles of incidence  $\theta_o^1$ , the spread in the values of the like backscatter cross sections is more pronounced for the horizontally polarized waves than for the vertically polarized waves. The reason for this is found

by examining the expression for the dominant term at large angles  $\theta_o^1$ , i.e.,  $\langle \sigma^{PQ} \rangle_{R1}$  (first order Bragg). In this term  $|v_y^D{}^{HH}|^2$  is proportional to  $|\bar{n}^1 \cdot \bar{n}|^4$  while  $|v_y^D{}^{VV}|^2$  is proportional to  $|2 - (\bar{n}^1 \cdot \bar{n})^2|^2$ . The latter term is both larger and less sensitive to slope variations  $\bar{n}(h_x, h_z)$ . In Figs. 8a,b,c,d and 9a,b,c,d,  $\langle \sigma^{VV} \rangle_T$  the total backscatter cross sections,  $\langle \sigma^{VV} \rangle_o$  the large scale backscatter cross section  $\langle \sigma^{VV} \rangle_{R1}$ , the leading term of the small scale cross section (which corresponds to first order Bragg scatter) and the remainder term  $\langle \sigma^{VV} \rangle_{R2} + \langle \sigma^{VV} \rangle_{R3}$  are plotted as functions of  $\theta_o^1$ , case (a)  $k = 1$ , case (b)  $k = 2$ , case (c)  $k = 5$ , case (d) Gaussian surface heights. The results for  $k = 25$  are not shown since they are indistinguishable from the results for the Gaussian surface). In Figs. 8a,b,c,d,  $\sigma_{lt}^2 = 0.0171$  and in Figs. 9a,b,c,d  $\sigma_{lt}^2 = 0.0564$ . The corresponding results for  $\sigma^{HH}$  and  $\sigma^{HV} = \sigma^{VH}$  are presented in Figs. 10a,b,c,d and 11a,b,c,d, 12a,b,c,d and 13a,b,c,d. From the above plots of the backscatter cross section it is seen that not only is the total backscatter cross section  $\langle \sigma^{PQ} \rangle_T$  sensitive to changes in values of  $k$ , but the individual terms in the weighted sum (2.7) are also sensitive to changes in  $k$ . Furthermore, except for near grazing angles the backscatter cross section for the small scale surface  $\langle \sigma^{PQ} \rangle_R$  cannot be approximated by the leading term in the series (2.13) which corresponds to first order Bragg scatter. It has been shown using the full wave approach, Bahar et al. (1982), that the total backscatter cross section  $\langle \sigma^{PQ} \rangle_T$  is independent of the specific choice of  $k_d$  for  $\beta \geq 1$  provided none of the significant terms in (2.13) are neglected. The terms  $\langle \sigma^{PQ} \rangle_{Rm}$ , for  $m \geq 4$ , can be neglected for all  $\theta_o$  when  $k_d$  is chosen such that  $\beta = 1$ .

On the basis of the above results, several schemes can be devised to distinguish between the backscatter cross sections for different values of  $k$ .

The behavior of  $\langle \sigma^{PP} \rangle_T$  ( $P=V,H$ ) near normal incidence is of particular interest in this respect. Thus one notices that  $\left| d\langle \sigma^{PP} \rangle / d\theta_o^1 \right|_{\theta_o^1=0}$  is largest for  $k = 1$  and decreases gradually as  $k$  increases. Since  $\langle \sigma^{HH} \rangle_T$  is more sensitive to variations in  $k$  for  $\theta_o > 25^\circ$ , the backscatter cross sections for horizontally polarized waves are more indicative of the particular form of the rough surfaces height distribution than the backscatter cross sections for the vertically polarized waves. The depolarized backscatter cross sections  $\langle \sigma^{PQ} \rangle$  ( $P \neq Q$ ) are rather insensitive to the particular form of the rough surface height distribution except near normal incidence where  $\left| d\langle \sigma^{PQ} \rangle / d\theta_o \right|_{\theta_o=0}$  is largest for  $k = 1$ .

## 6. Concluding Remarks

Full wave expressions for the like polarized and the depolarized scattering cross sections are derived for a broad family of non-Gaussian rough surfaces. It is assumed that when the surface heights decorrelate they become statistically independent. For the cases considered in the illustrative examples, it is shown that while the shadow functions are not very sensitive to the parameter  $k(=1,2,3,\dots)$  of the surface height probability density assumed, the backscatter cross sections are sensitive to the parameter  $k$ .

The like polarized backscatter cross sections  $\langle \sigma^{VV} \rangle_T$  and  $\langle \sigma^{HH} \rangle_T$  have the same dependence on  $k$  for small angles of incidence  $\theta_o^1$ , however for large angles  $\theta_o^1$ , the cross section  $\langle \sigma^{HH} \rangle_T$  is much more sensitive to  $k$  than  $\langle \sigma^{VV} \rangle_T$ . An examination of the expression for the dominant term corresponding to first order Bragg scatter  $\langle \sigma^{PP} \rangle_{R1}$  provides an explanation to this phenomenon. The depolarized backscatter cross sections  $\langle \sigma^{PQ} \rangle_T$  ( $P \neq Q$ ) are sensitive to  $k$  only near normal



incidence. For  $\theta_0^1 = 0$ , the like polarized cross section  $\langle \sigma^{PP} \rangle_T$  is largest for the smallest value of  $k$  ( $k = 1$ ). This is because the slope probability density for zero slope is largest when  $k = 1$ . Thus consistent with energy conservation as the like polarized cross section increases with decreasing  $k$  values, the depolarized cross section decreases with decreasing  $k$  values. Both the total backscatter cross sections and the components of the weighted sum of cross sections are presented in Section 5. The terms corresponding to  $\langle \sigma^{PQ} \rangle_{Rm}$   $m \geq 2$  cannot be neglected in this work and a perturbed physical optics approach is not suitable for determining the total backscatter cross section (Bahar et al. 1982).

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# Figure Captions

Figure 1. Plane of incidence, scattering plane, and reference (x,z) plane.

Figure 2. Local plane of incidence and scatter and local coordinate system with unit vectors  $\bar{n}_1, \bar{n}_2, \bar{n}_3$ .

Figure 3. The one dimensional gamma surface height distributions times  $\sigma$  as functions of  $h/\sigma$  for  $k = 1, 2, 5, 25$  together with the Gaussian surface height distribution with  $\langle h \rangle / \sigma = 5$ .

( $\square$ )  $k = 1$ , ( $\Delta$ )  $k = 2$ , (+)  $k = 5$ , (X)  $k = 25$ , ( $\diamond$ ) Gaussian.

Figure 4. The one dimensional slope distributions times  $\sigma_{lt} = \sqrt{2} \sigma_x$  as functions of  $h_x / \sigma_{lt}$ . ( $\square$ )  $k = 1$ , ( $\Delta$ )  $k = 2$ , (+)  $k = 5$ , (X)  $k = 25$ , ( $\diamond$ ) Gaussian.

Figure 5. The shadow functions of functions of  $\theta_o^1$  for backscatter.

$\sigma_{lt}^2 = 0.0171$  and  $\sigma_{lt}^2 = 0.0564$  ( $\square$ )  $k = 1$ , ( $\Delta$ )  $k = 2$ , (+)  $k = 5$ , (X)  $k = 25$ , ( $\diamond$ ) Gaussian.

Figure 6. The total backscatter cross sections (2.7) as functions of  $\theta_o^1$  for  $\sigma_{lt}^2 = 0.0171$

(a)  $\langle \sigma^{VV} \rangle$  (b)  $\langle \sigma^{HH} \rangle$  (c)  $\langle \sigma^{VH} \rangle = \langle \sigma^{HV} \rangle$ .

( $\square$ )  $k = 1$ , ( $\Delta$ )  $k = 2$ , (+)  $k = 5$ , (X)  $k = 25$ , ( $\diamond$ ) Gaussian.

Figure 7. The total backscatter cross sections (2.7) as functions of  $\theta_o^1$  for  $\sigma_{lt}^2 = 0.0564$

(a)  $\langle \sigma^{VV} \rangle$  (b)  $\langle \sigma^{HH} \rangle$  (c)  $\langle \sigma^{VH} \rangle = \langle \sigma^{HV} \rangle$

( $\square$ )  $k = 1$ , ( $\Delta$ )  $k = 2$ , (+)  $k = 5$ , (X)  $k = 25$ , ( $\diamond$ ) Gaussian.

Figure 8. Backscatter cross sections  $(-)\langle \sigma^{VV} \rangle_T, (X)\langle \sigma^{VV} \rangle_o, (\square)\langle \sigma^{VV} \rangle_{R1}, (\Delta)\langle \sigma^{VV} \rangle_{R2} + \langle \sigma^{VV} \rangle_{R3}$  as functions of  $\theta_o^1$  for  $\sigma_{lt}^2 = 0.0171$

(a)  $k = 1$ , (b)  $k = 2$ , (c)  $k = 5$ , (d) Gaussian

Figure 9. Backscatter cross sections  $(-)\langle \sigma^{VV} \rangle_T, (X)\langle \sigma^{VV} \rangle_o, (\square)\langle \sigma^{VV} \rangle_{R1}, (\Delta)\langle \sigma^{VV} \rangle_{R2} + \langle \sigma^{VV} \rangle_{R3}$  as functions of  $\theta_o^1$  for  $\sigma_{lt}^2 = 0.0564$

(a)  $k = 1$ , (b)  $k = 2$ , (c)  $k = 5$ , (d) Gaussian.

Figure 10. Backscatter cross sections  $(-)\langle\sigma_{\text{T}}^{\text{HH}}\rangle$ ,  $(X)\langle\sigma_{\text{O}}^{\text{HH}}\rangle$ ,  $(\square)\langle\sigma_{\text{R1}}^{\text{HH}}\rangle$ ,  
 $(\Delta)\langle\sigma_{\text{R2}}^{\text{HH}}\rangle + \langle\sigma_{\text{R3}}^{\text{HH}}\rangle$  as functions of  $\theta_{\text{O}}^1$  for  $\sigma_{\text{lt}}^2 = 0.0171$

(a)  $k = 1$ , (b)  $k = 2$ , (c)  $k = 5$ , (d) Gaussian

Figure 11. Backscatter cross sections  $(-)\langle\sigma_{\text{T}}^{\text{HH}}\rangle$ ,  $(X)\langle\sigma_{\text{O}}^{\text{HH}}\rangle$ ,  $(\square)\langle\sigma_{\text{R1}}^{\text{HH}}\rangle$ ,  
 $(\Delta)\langle\sigma_{\text{R2}}^{\text{HH}}\rangle + \langle\sigma_{\text{R3}}^{\text{HH}}\rangle$  as functions of  $\theta_{\text{O}}^1$  for  $\sigma_{\text{lt}}^2 = 0.0564$

(a)  $k = 1$ , (b)  $k = 2$ , (c)  $k = 5$ , (d) Gaussian.

Figure 12. Backscatter cross sections  $(-)\langle\sigma_{\text{T}}^{\text{VH}}\rangle$ ,  $(X)\langle\sigma_{\text{O}}^{\text{VH}}\rangle$ ,  $(\square)\langle\sigma_{\text{R1}}^{\text{VH}}\rangle$ ,  
 $(\Delta)\langle\sigma_{\text{R2}}^{\text{VH}}\rangle + \langle\sigma_{\text{R3}}^{\text{VH}}\rangle$  as functions of  $\theta_{\text{O}}^1$  for  $\sigma_{\text{lt}}^2 = 0.0171$

(a)  $k = 1$ , (b)  $k = 2$ , (c)  $k = 5$ , (d) Gaussian.

Figure 13. Backscatter cross sections  $(-)\langle\sigma_{\text{T}}^{\text{VH}}\rangle$ ,  $(X)\langle\sigma_{\text{O}}^{\text{VH}}\rangle$ ,  $(\square)\langle\sigma_{\text{R1}}^{\text{VH}}\rangle$ ,  
 $(\Delta)\langle\sigma_{\text{R2}}^{\text{VH}}\rangle + \langle\sigma_{\text{R3}}^{\text{VH}}\rangle$  as functions of  $\theta_{\text{O}}^1$  for  $\sigma_{\text{lt}}^2 = 0.0564$ .

(a)  $k = 1$ , (b)  $k = 2$ , (c)  $k = 5$ , (d) Gaussian.

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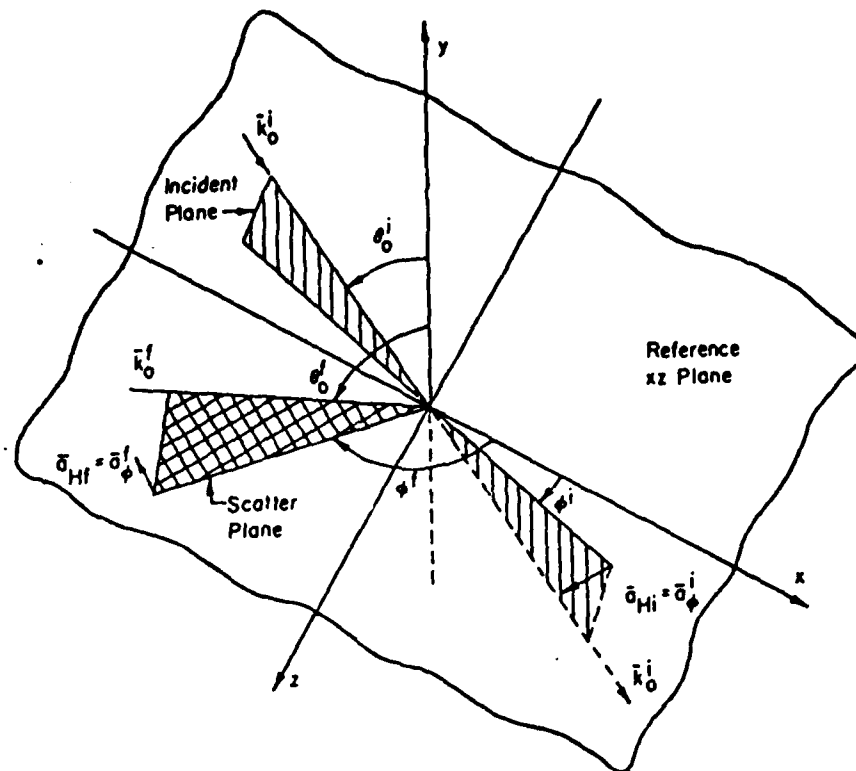


Fig. 1

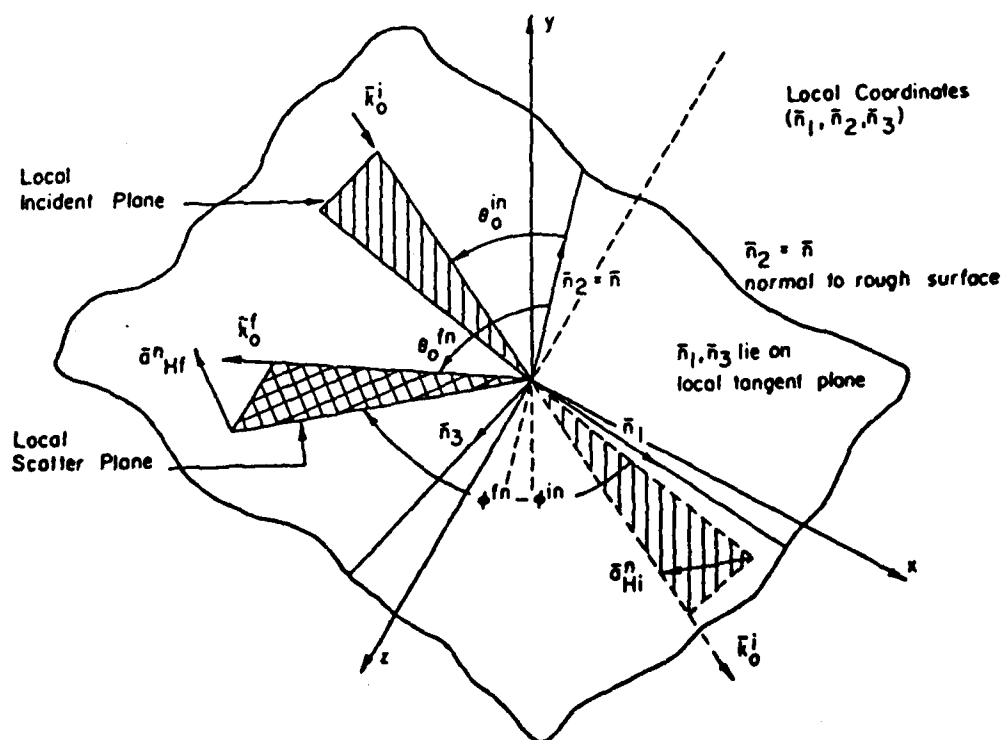


Fig. 2

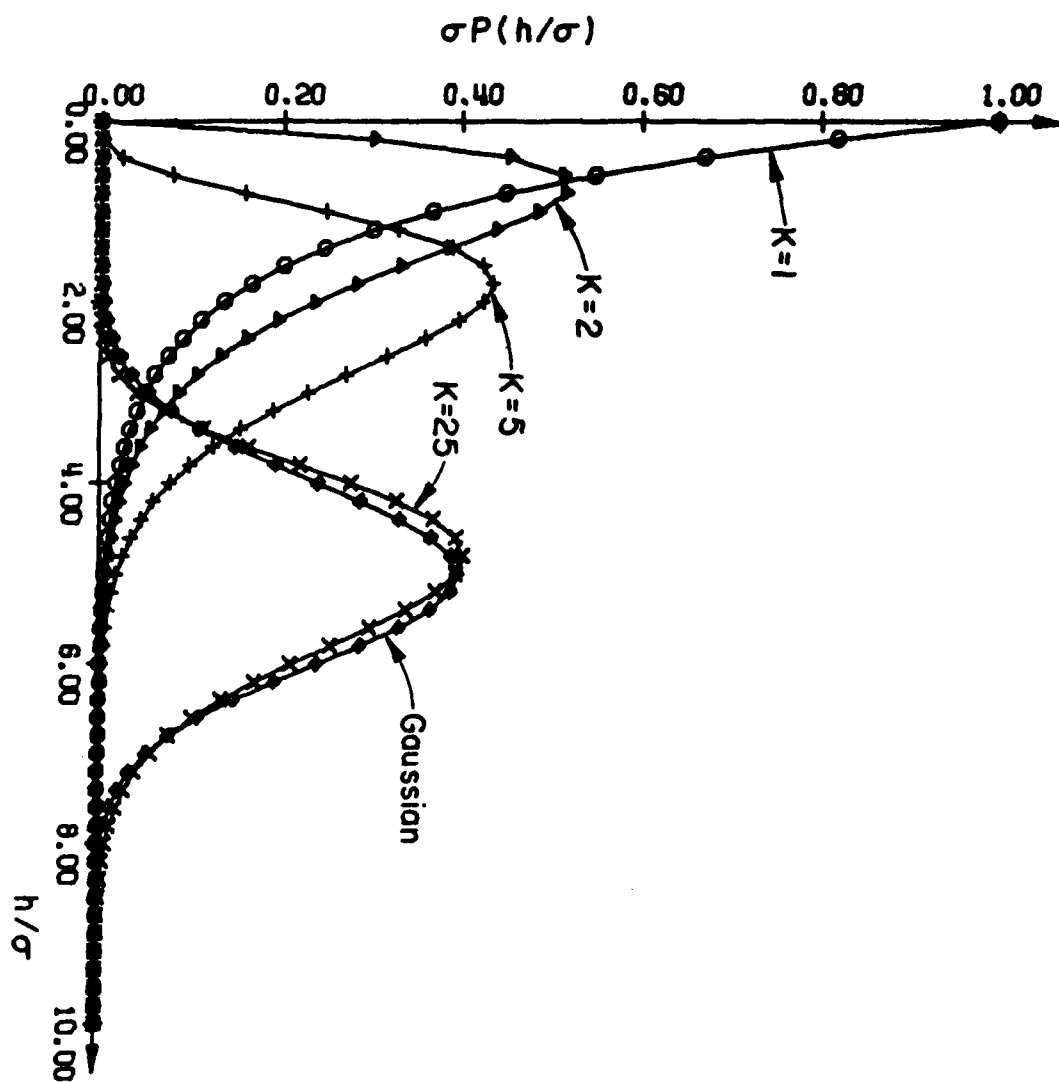


FIG. 3

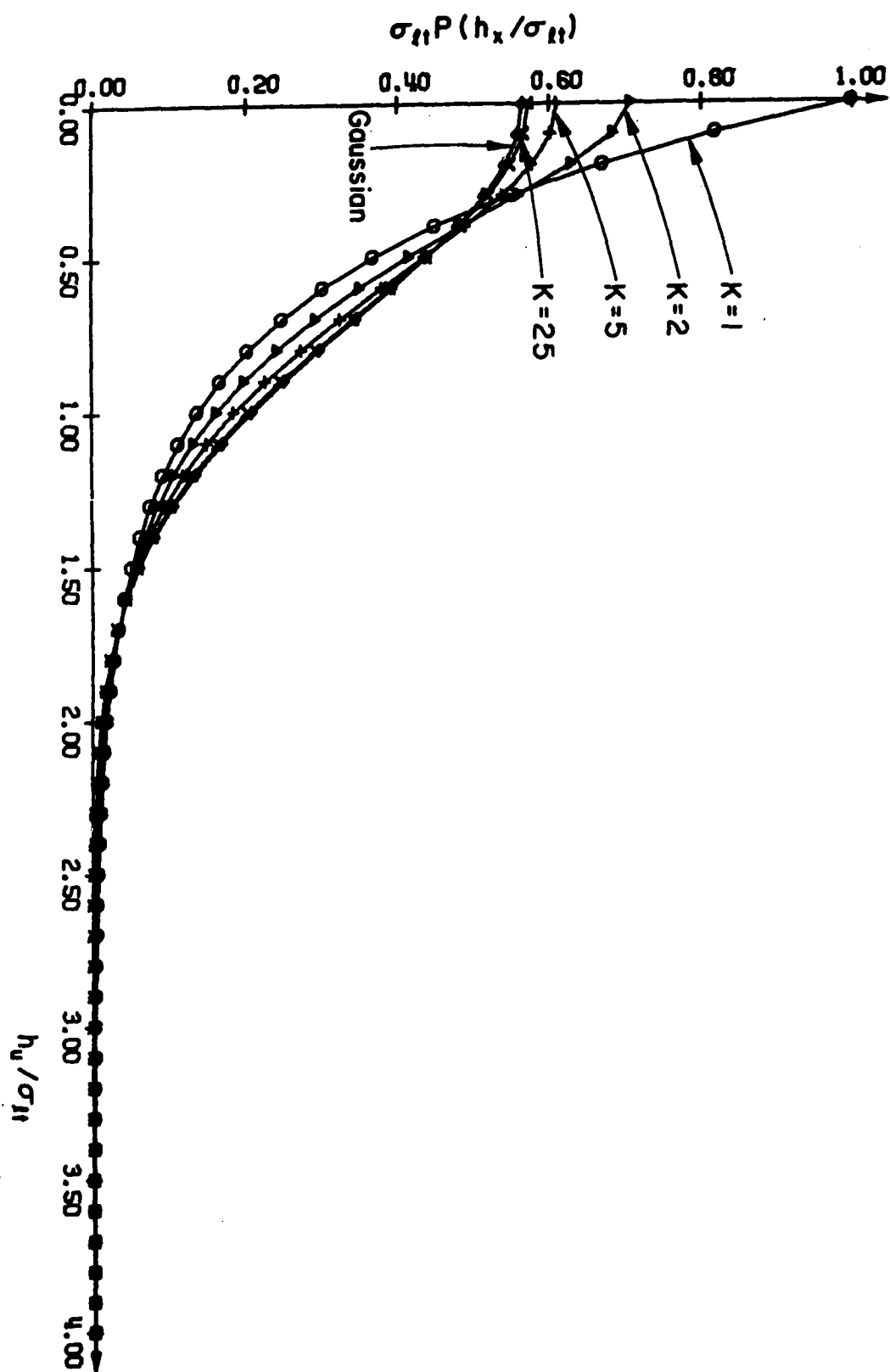
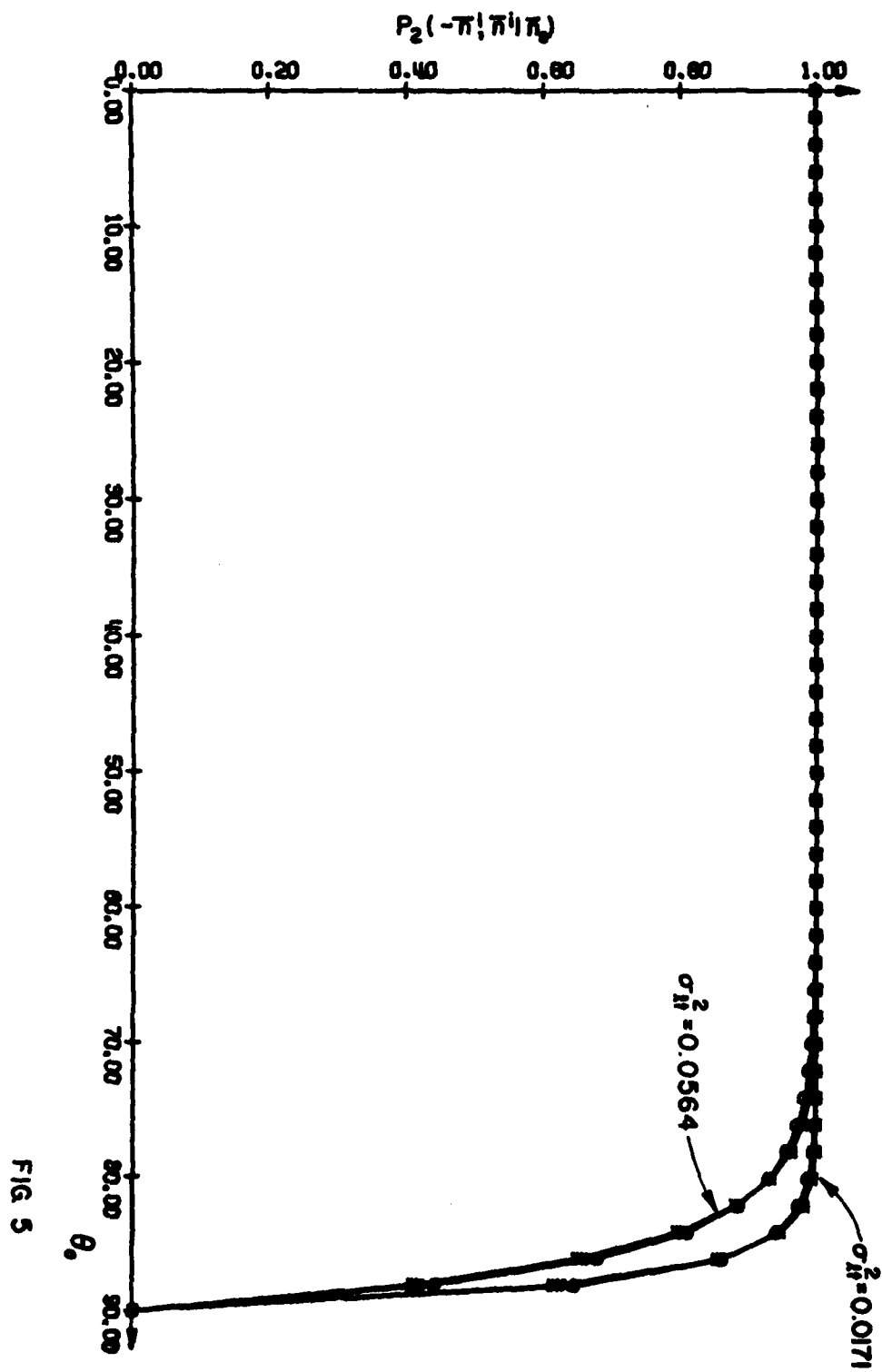


FIG. 4





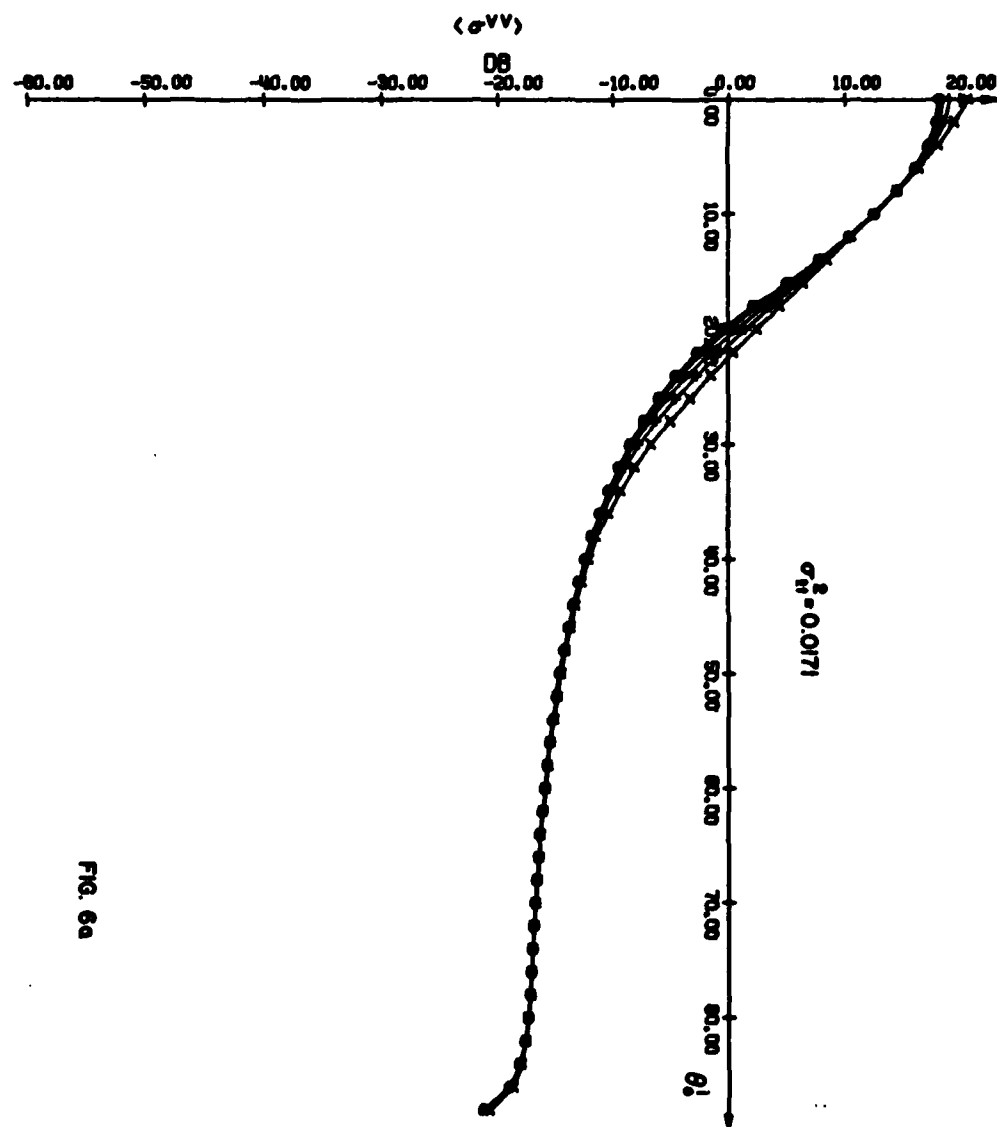


FIG. 6a

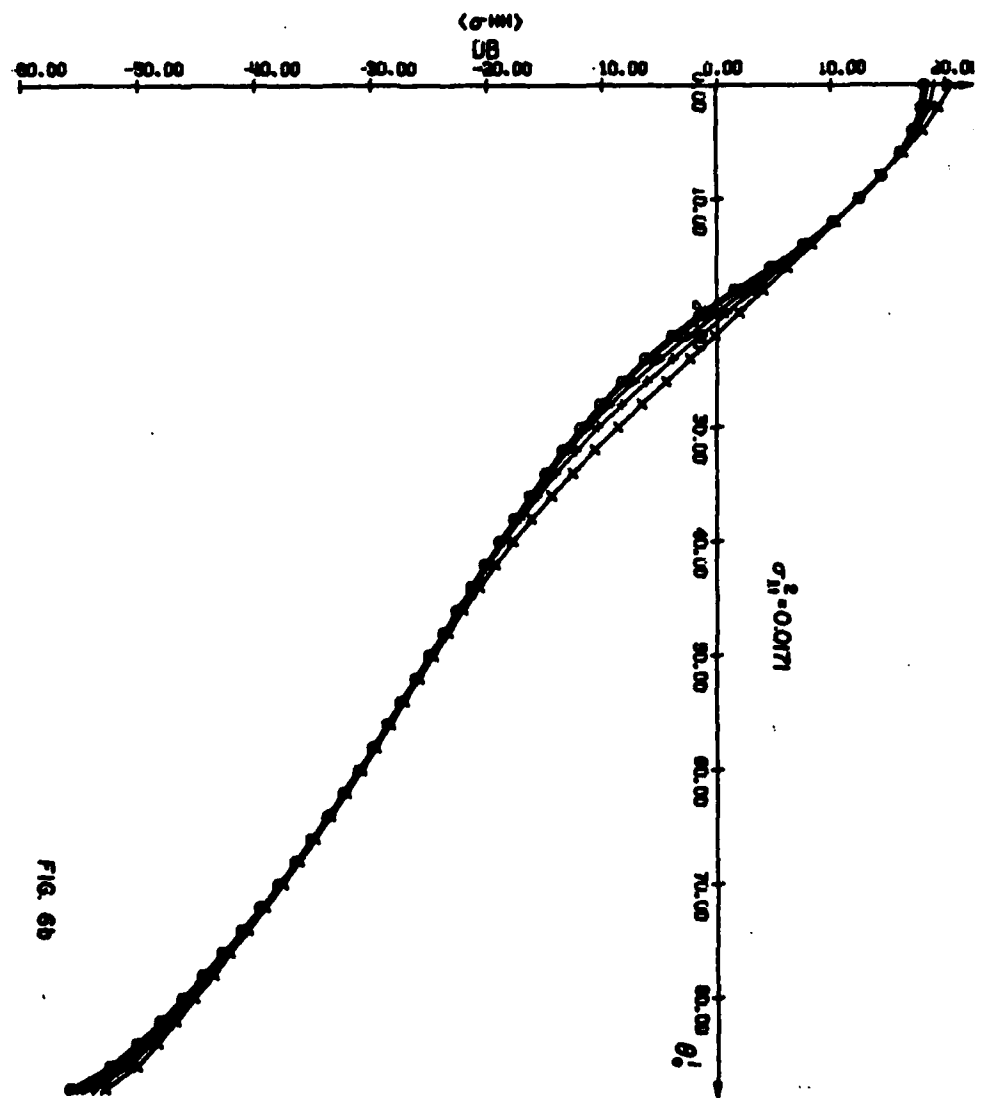


FIG. 6b

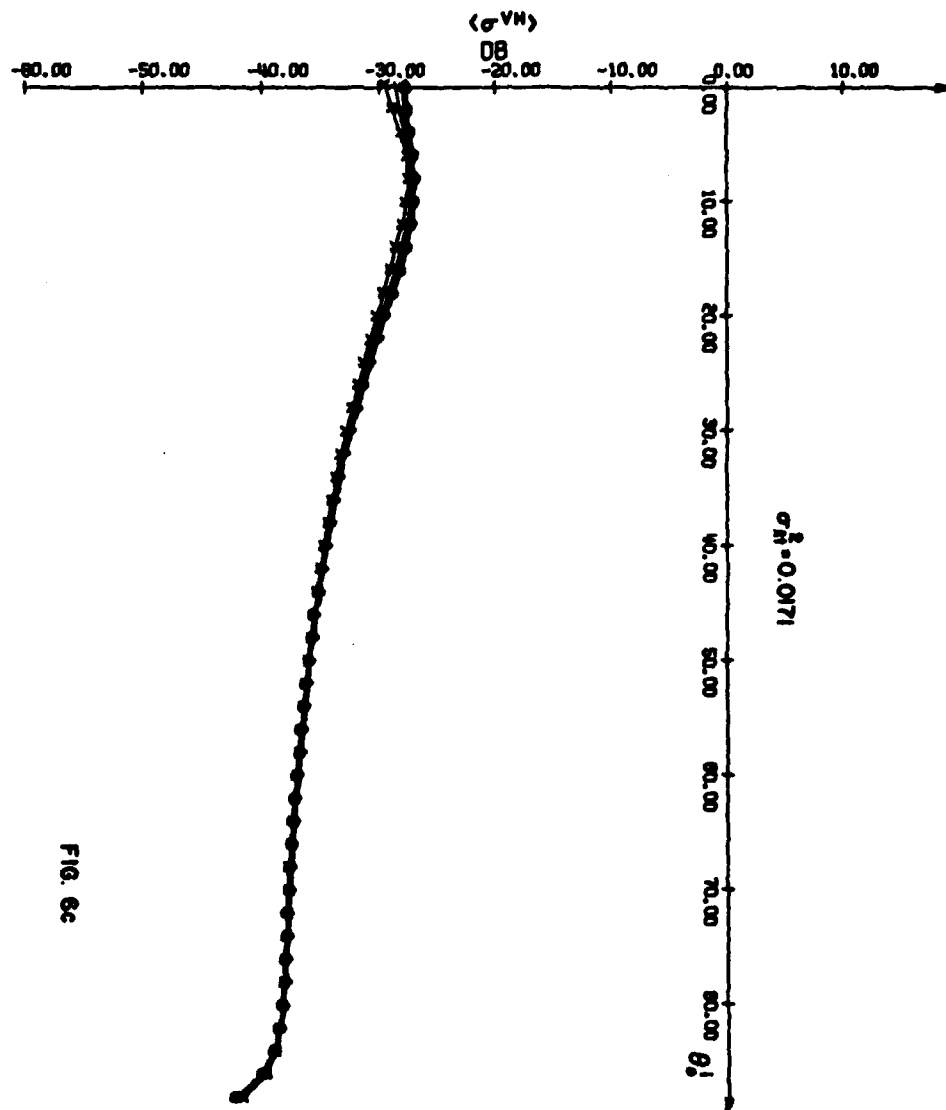


FIG. 6c

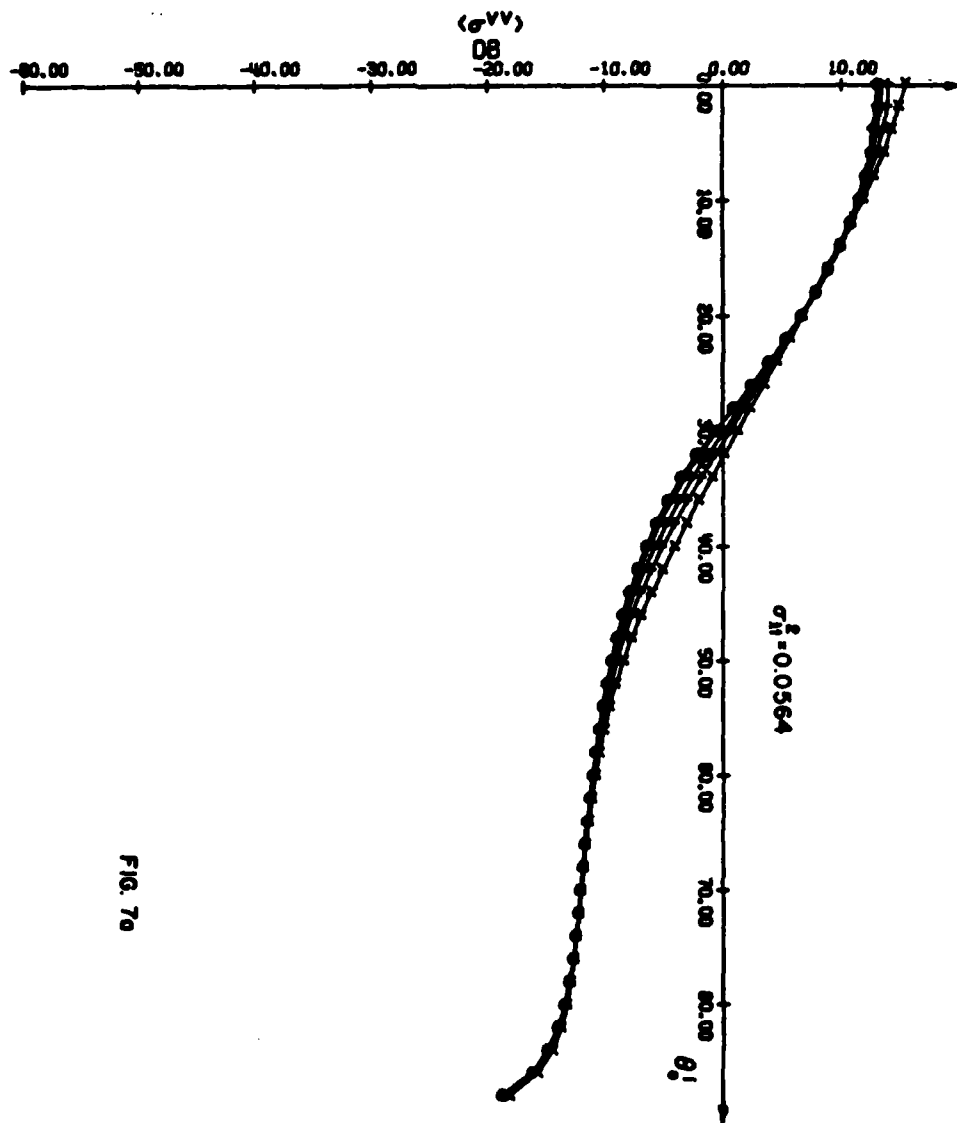


FIG. 70

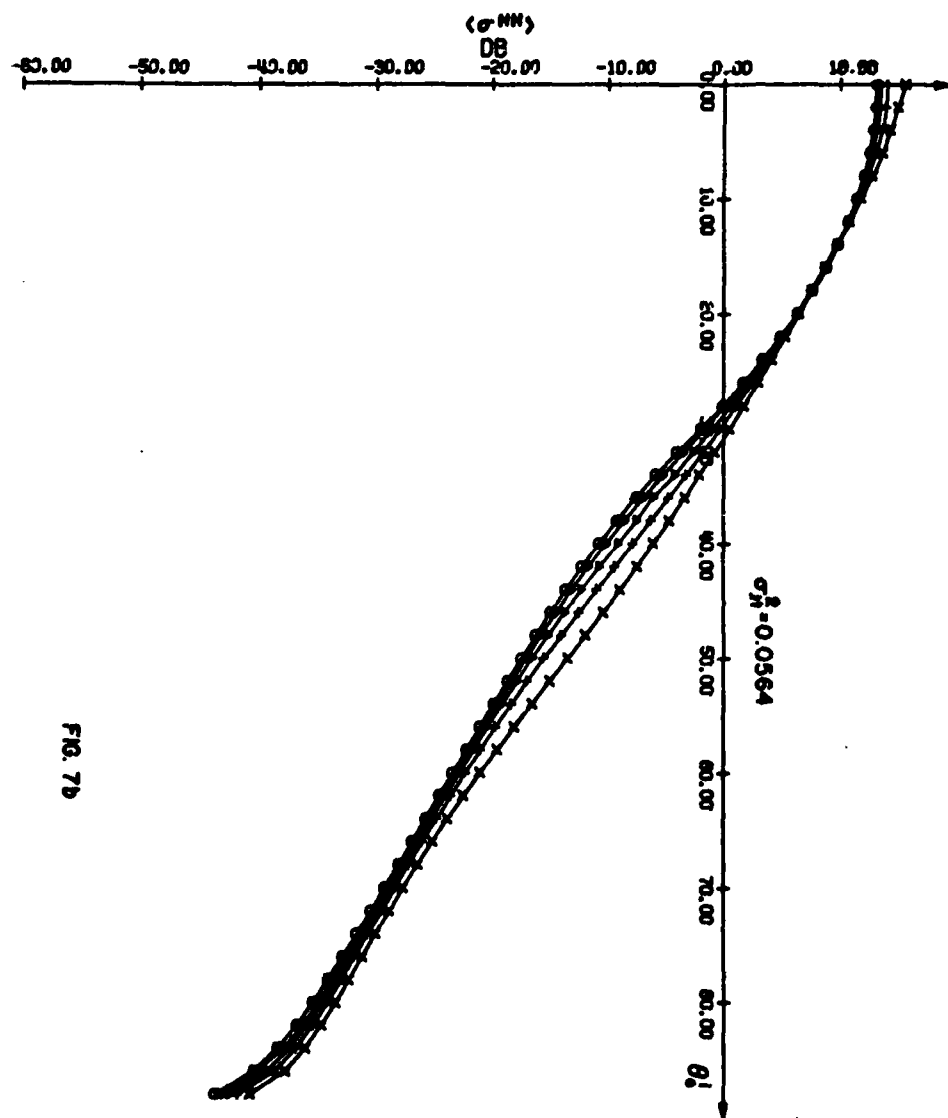


FIG. 7b

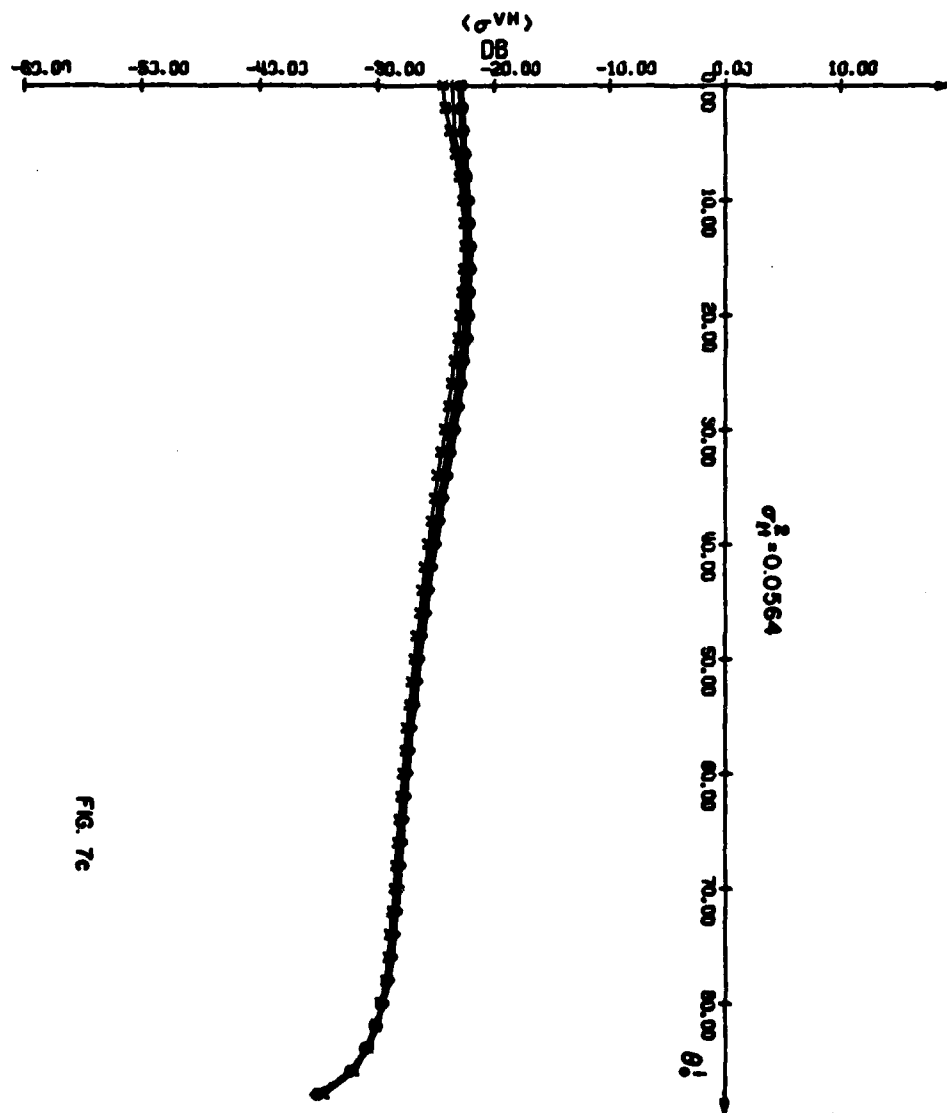


FIG. 7c

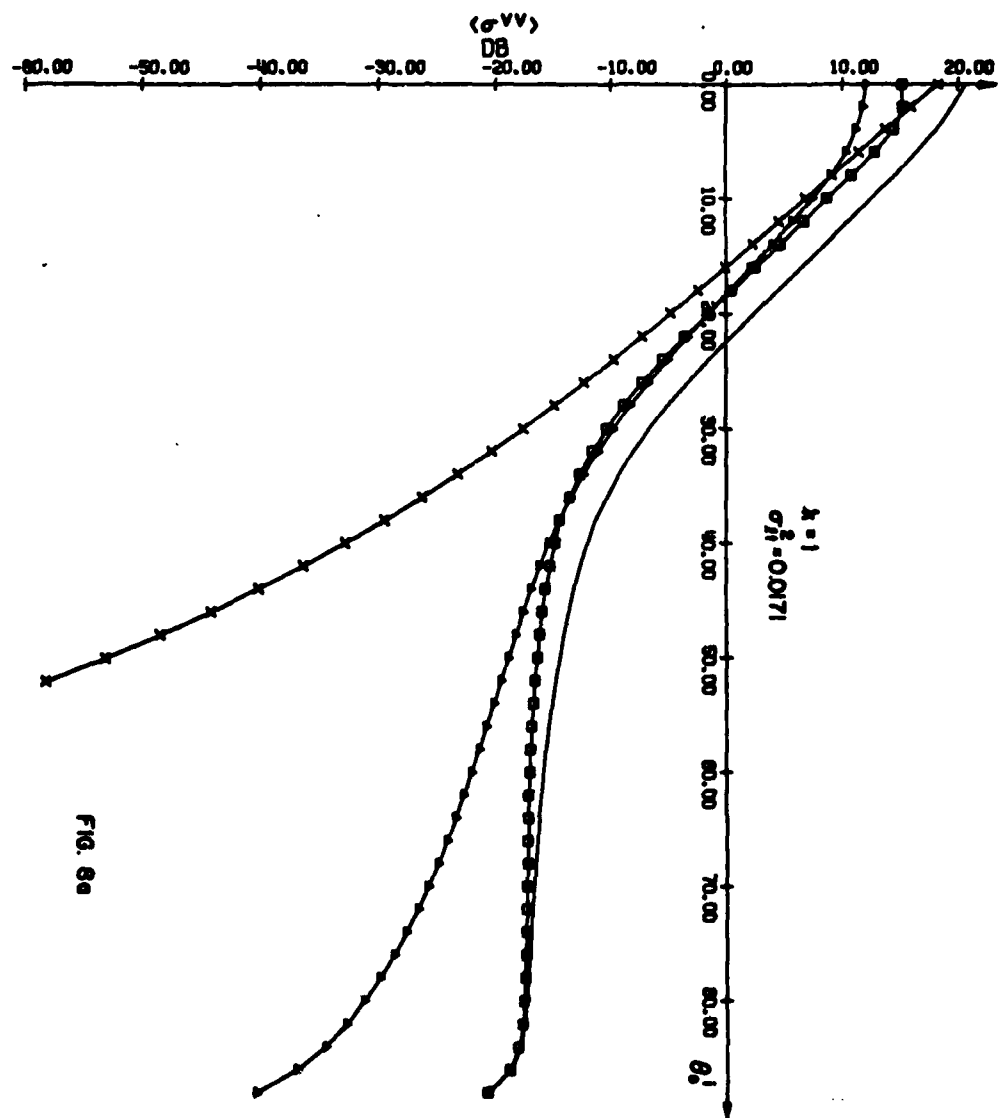


FIG. 8a

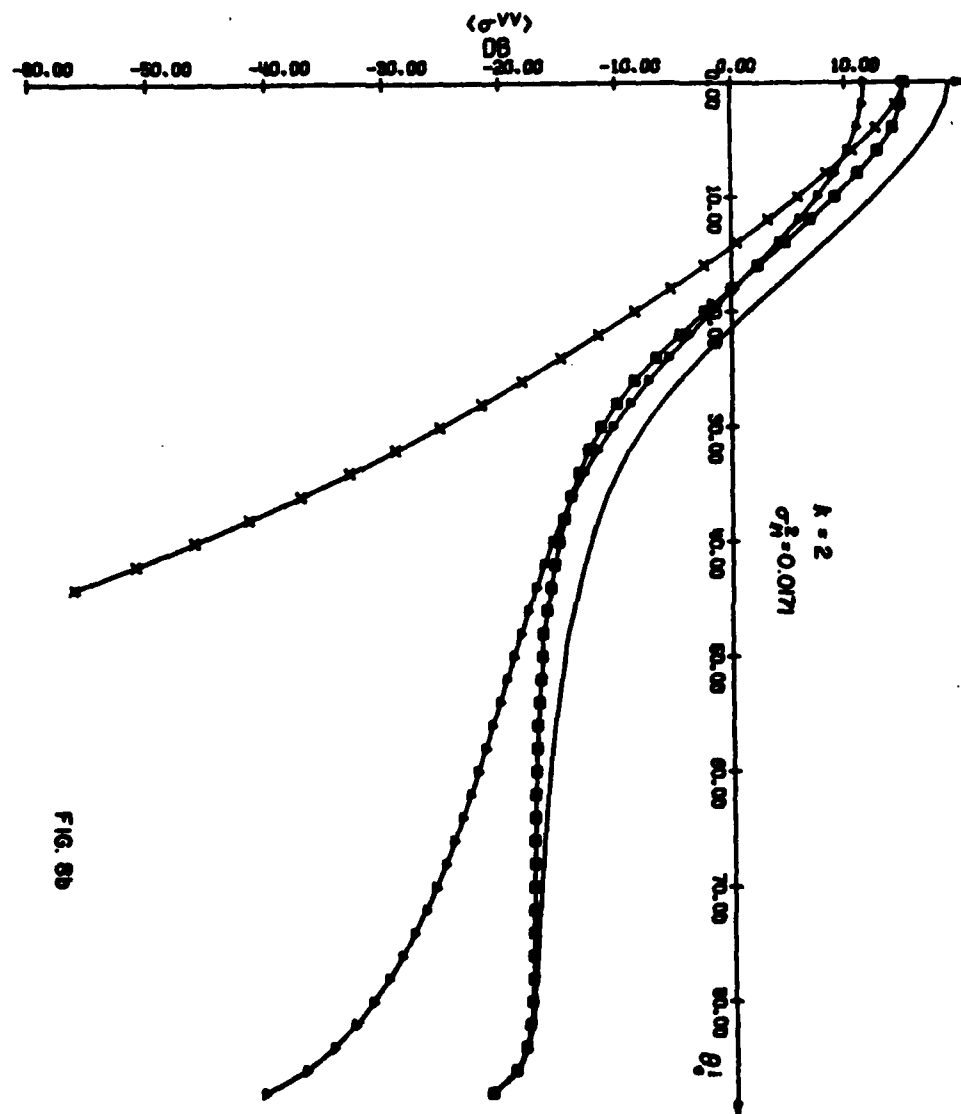


FIG. 8b



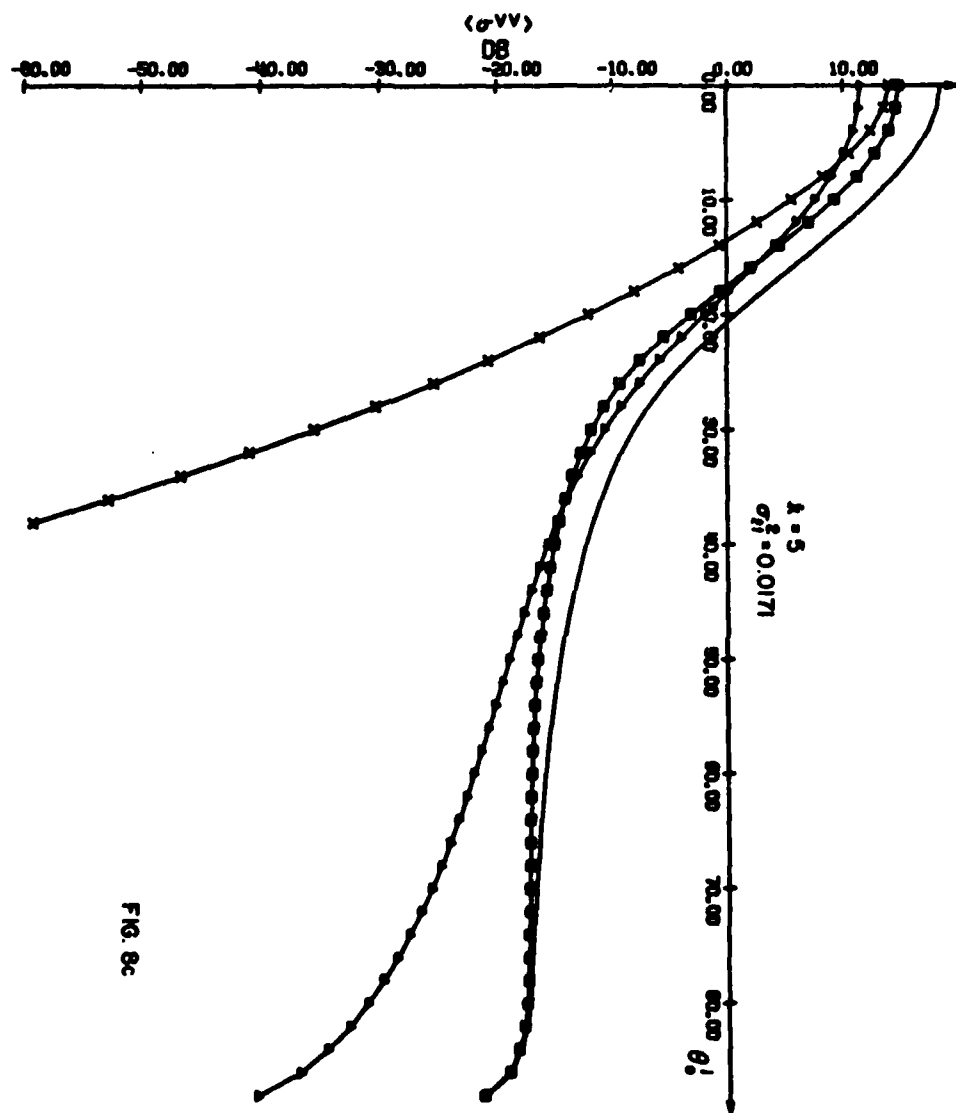


FIG. 8c

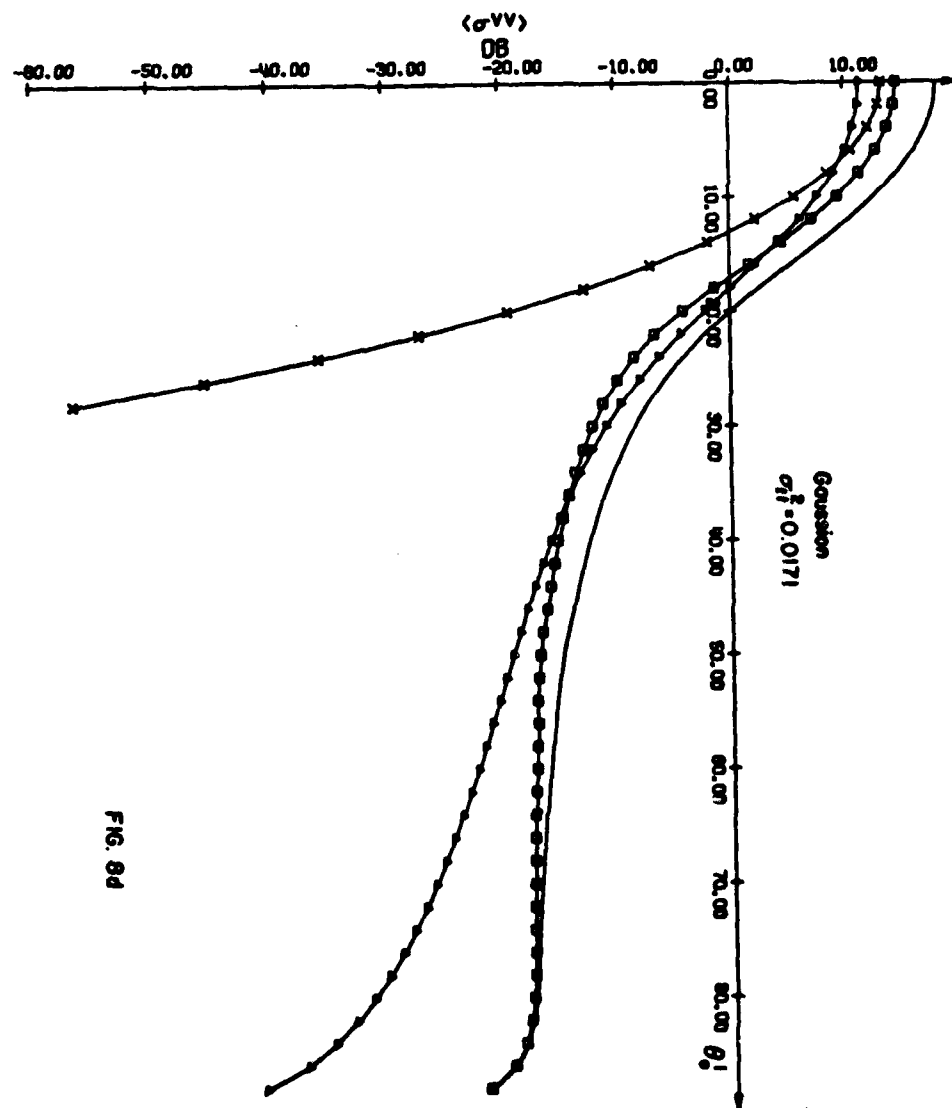


FIG. 8d

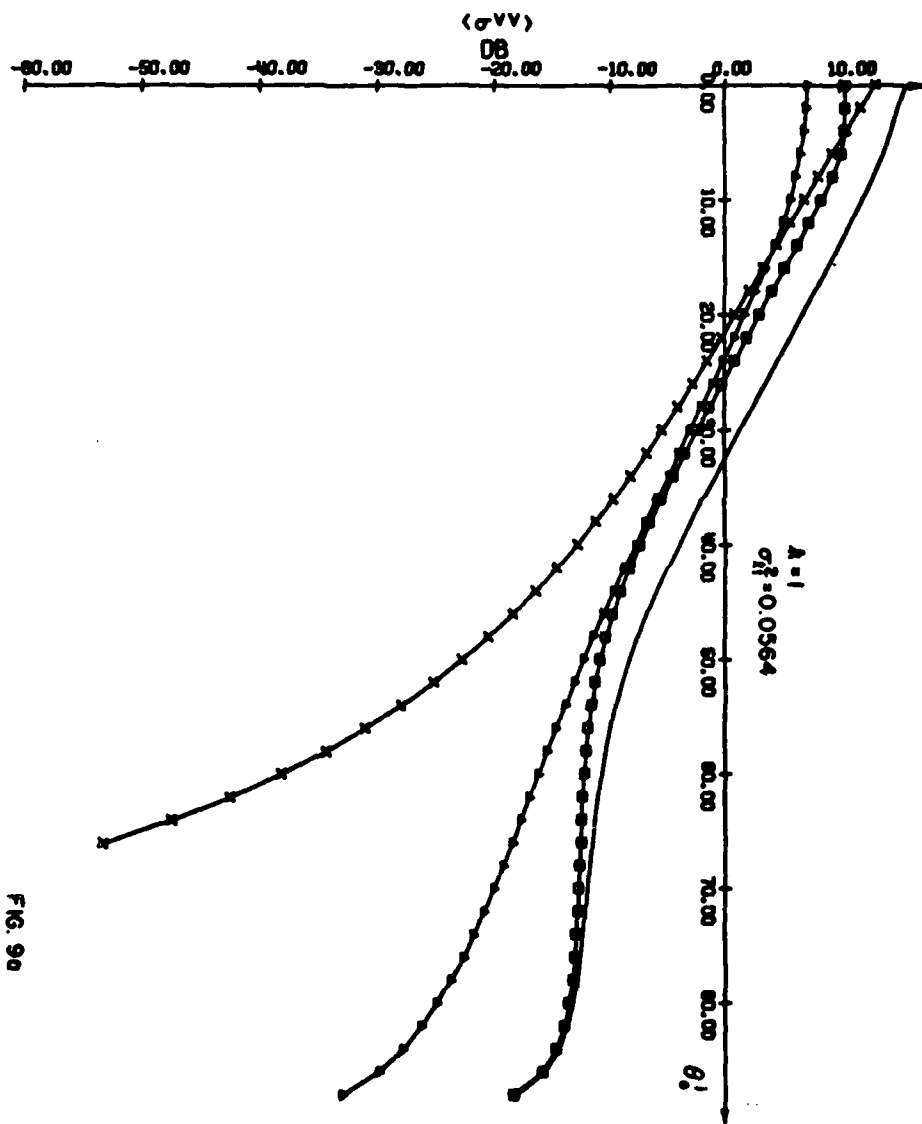


FIG. 9a

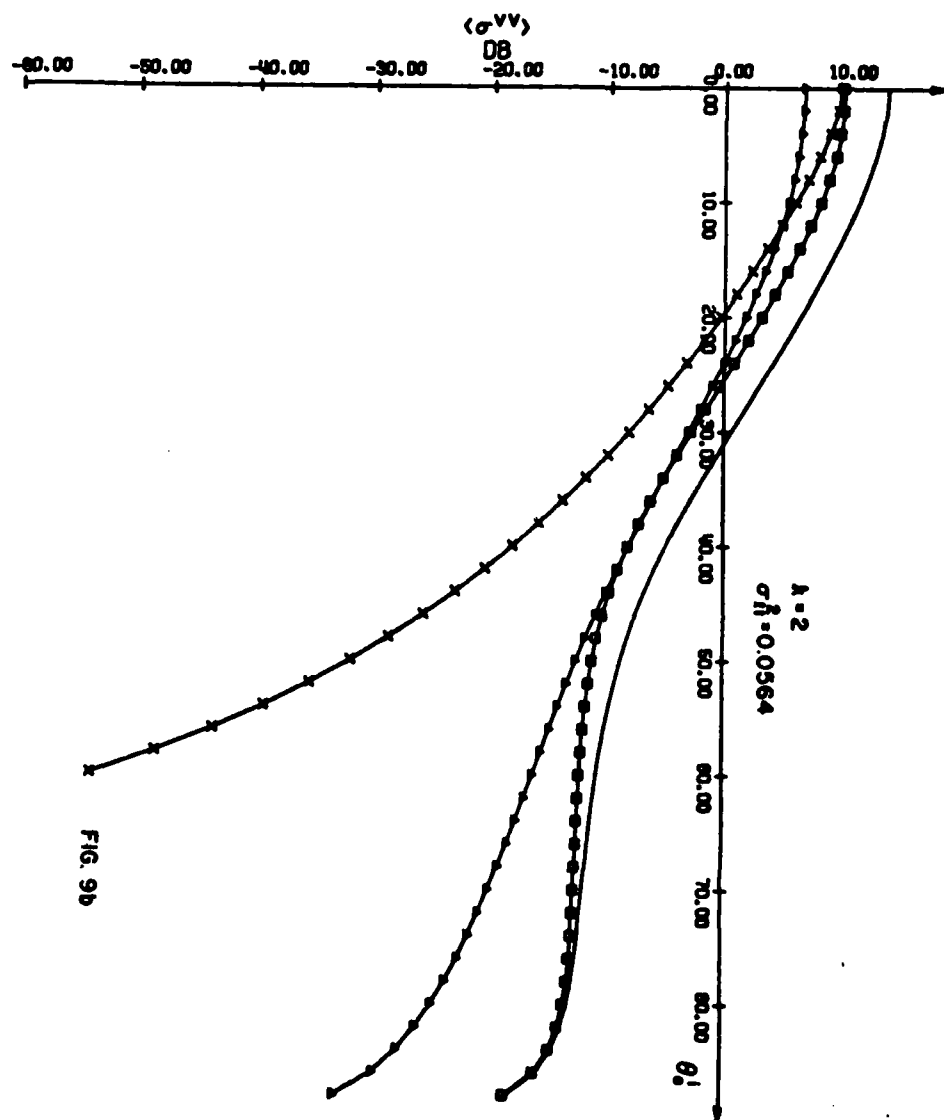


FIG. 9b

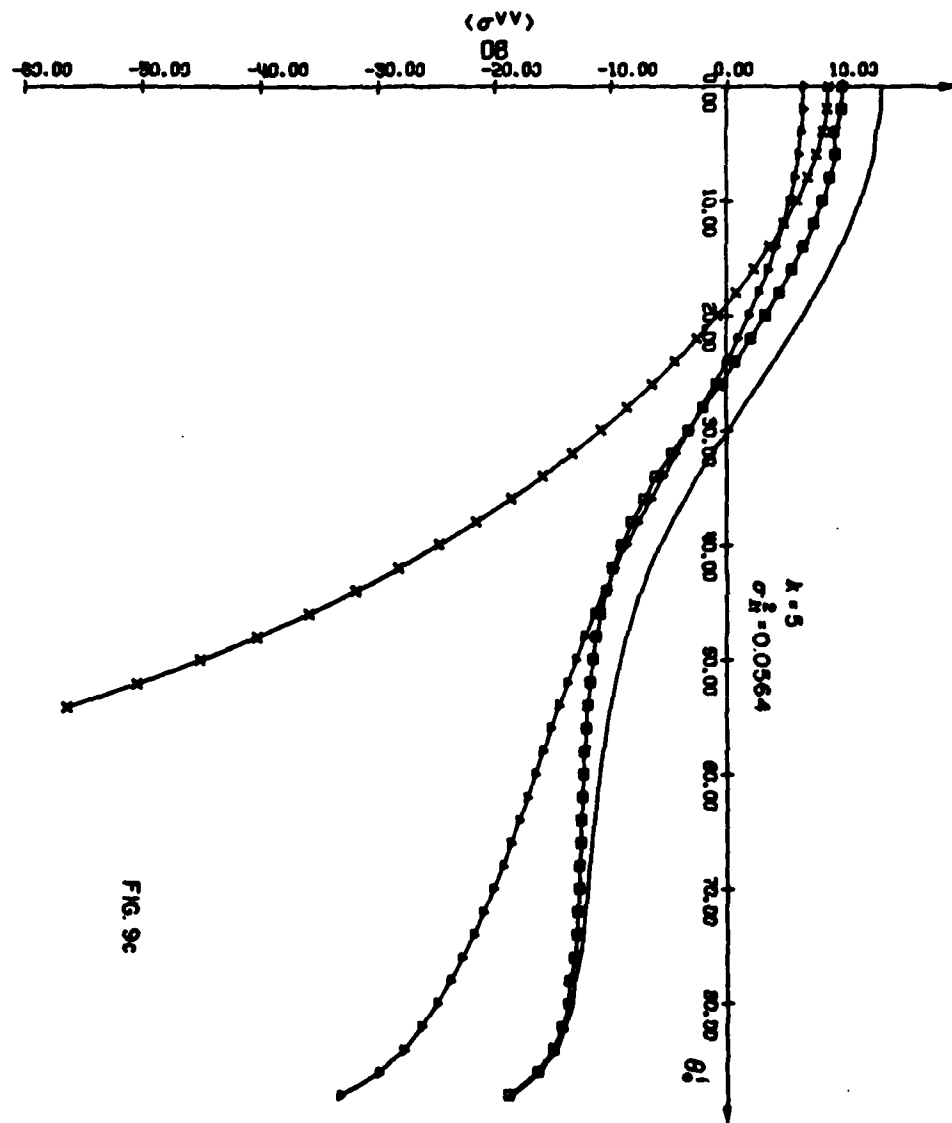


FIG. 9c

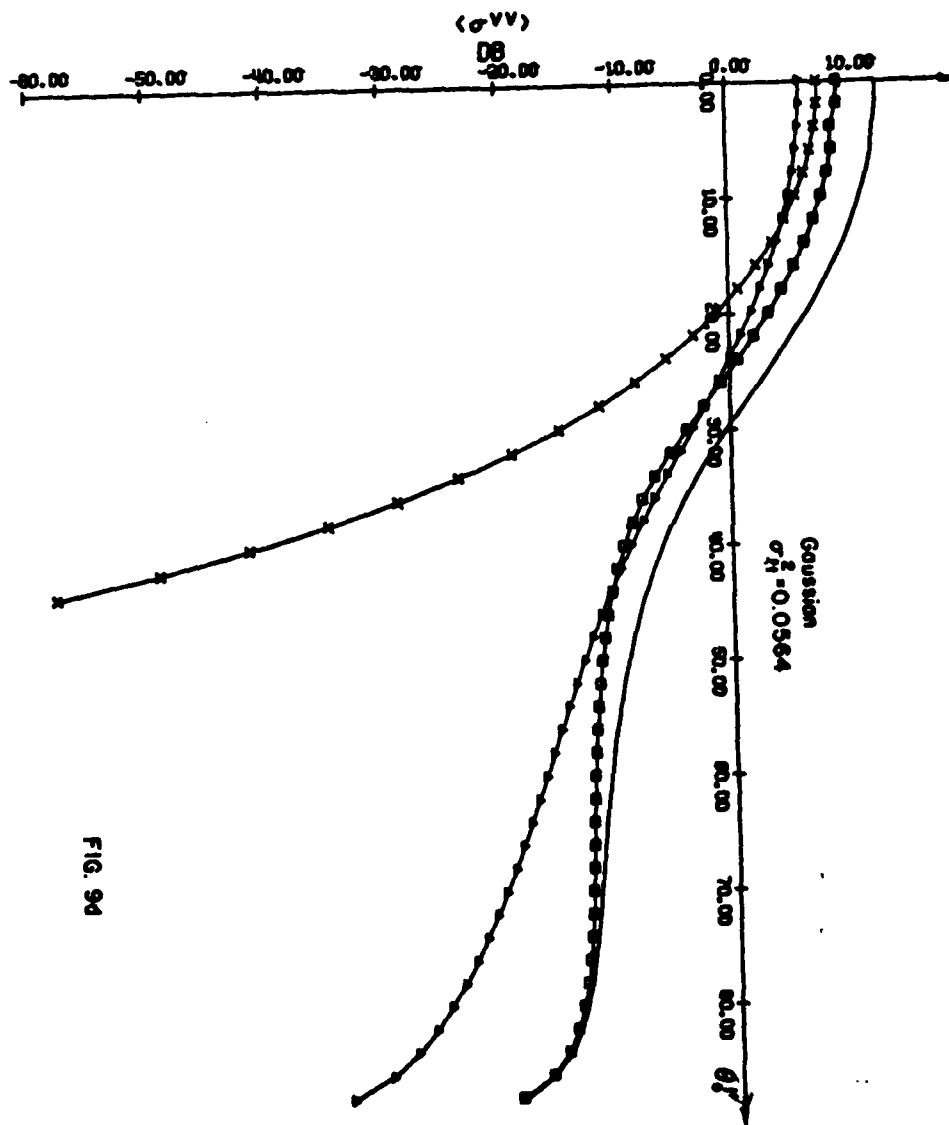


FIG. 94

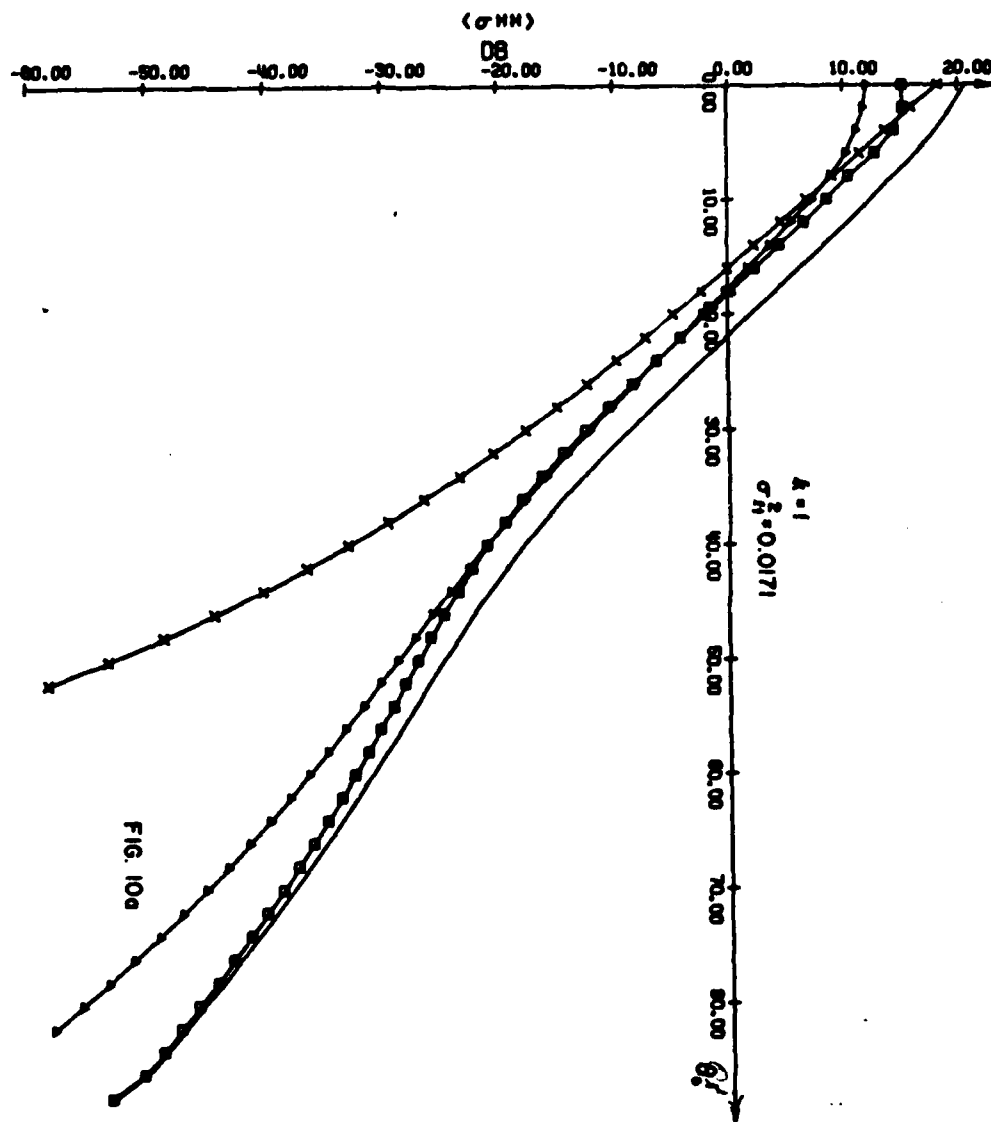
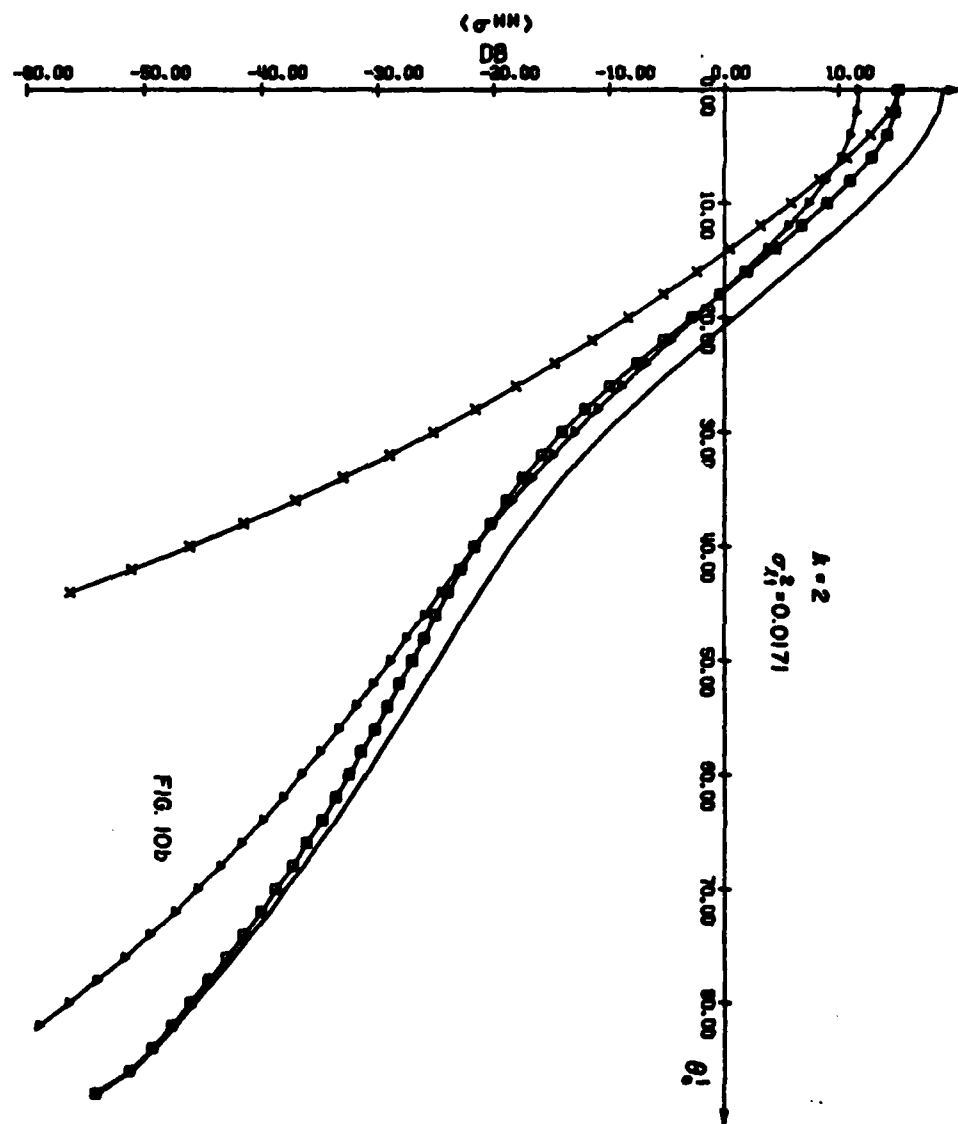


FIG. 10a





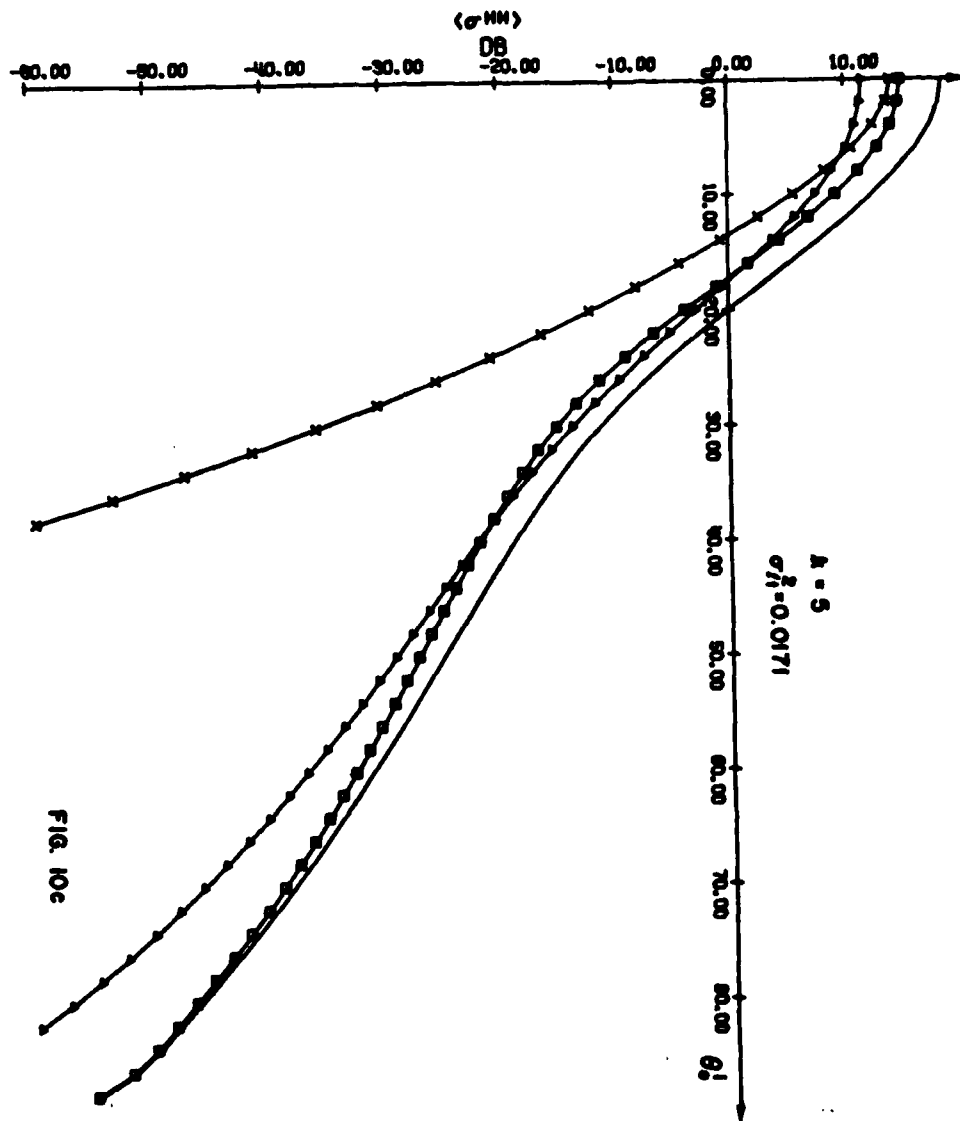


FIG. 10c

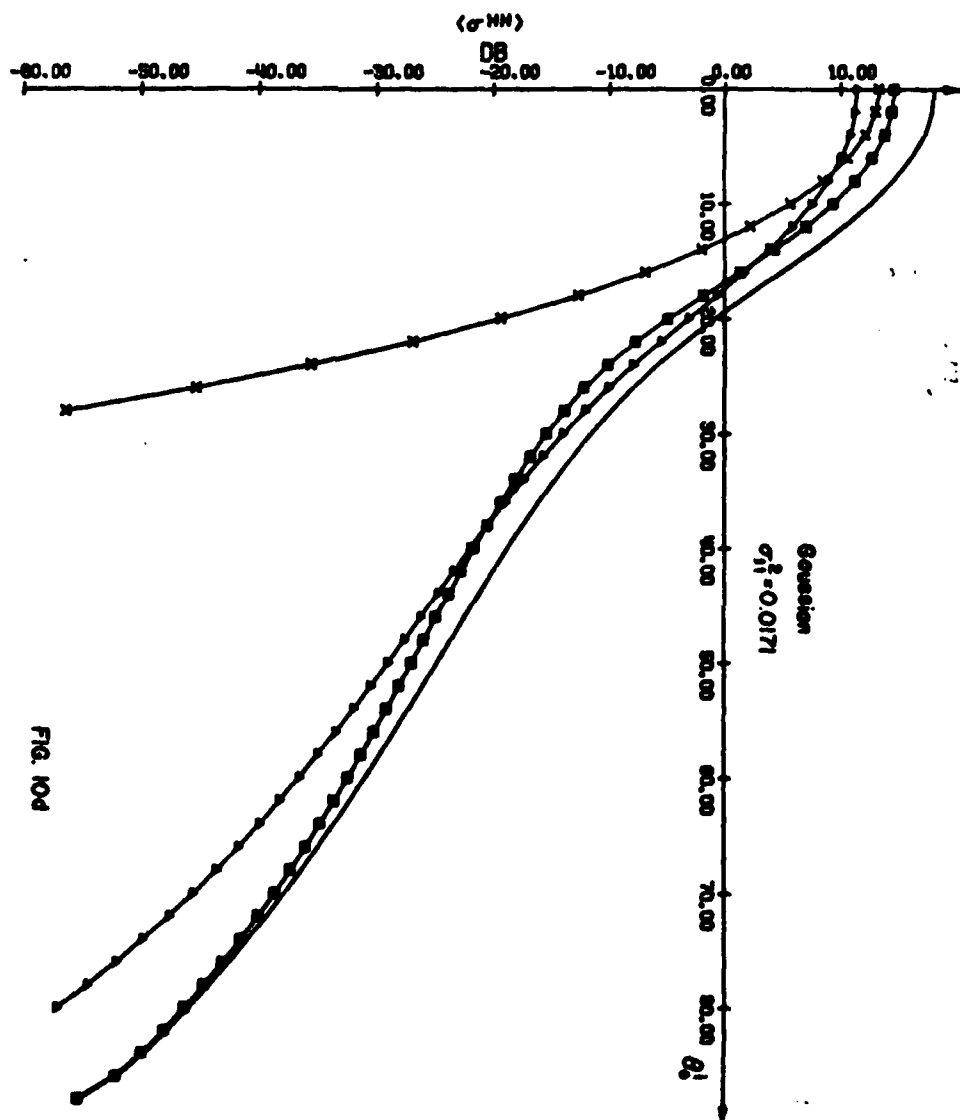


FIG. 104

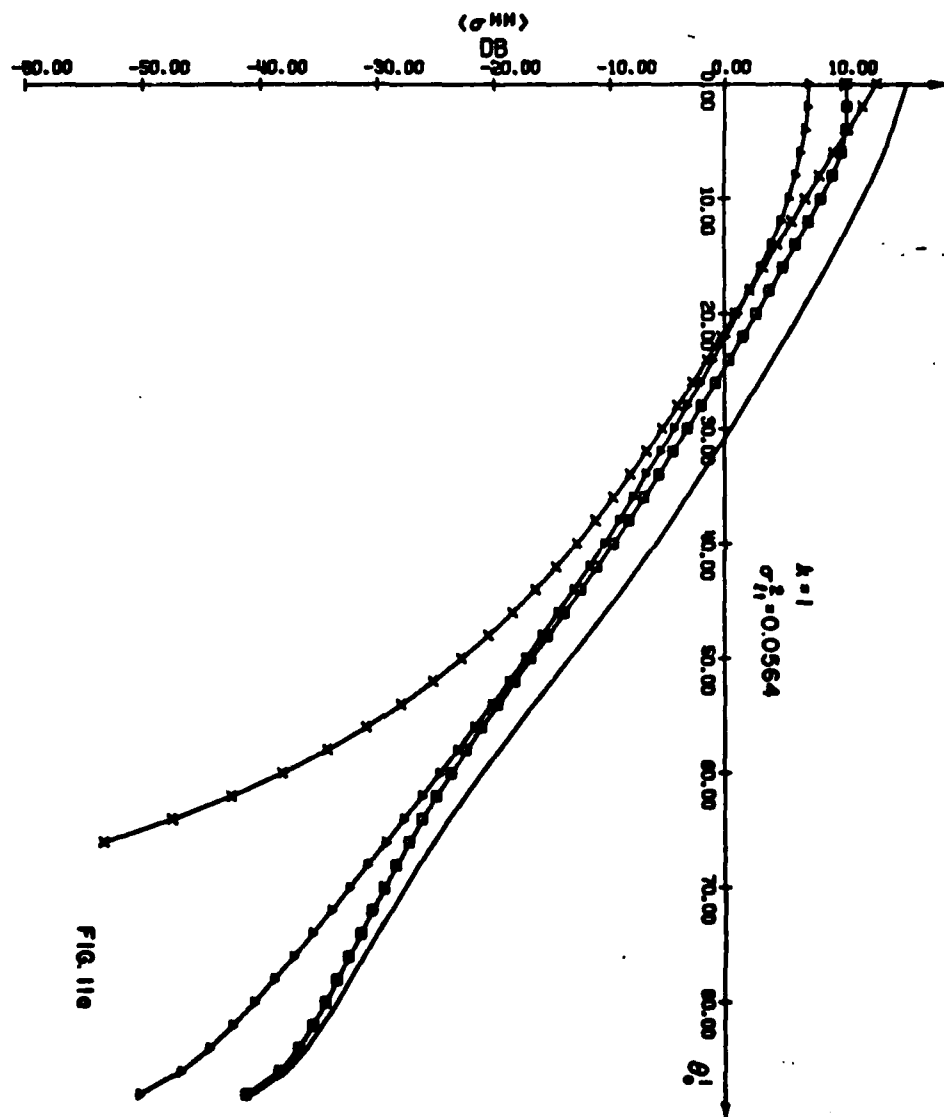


FIG. 11e

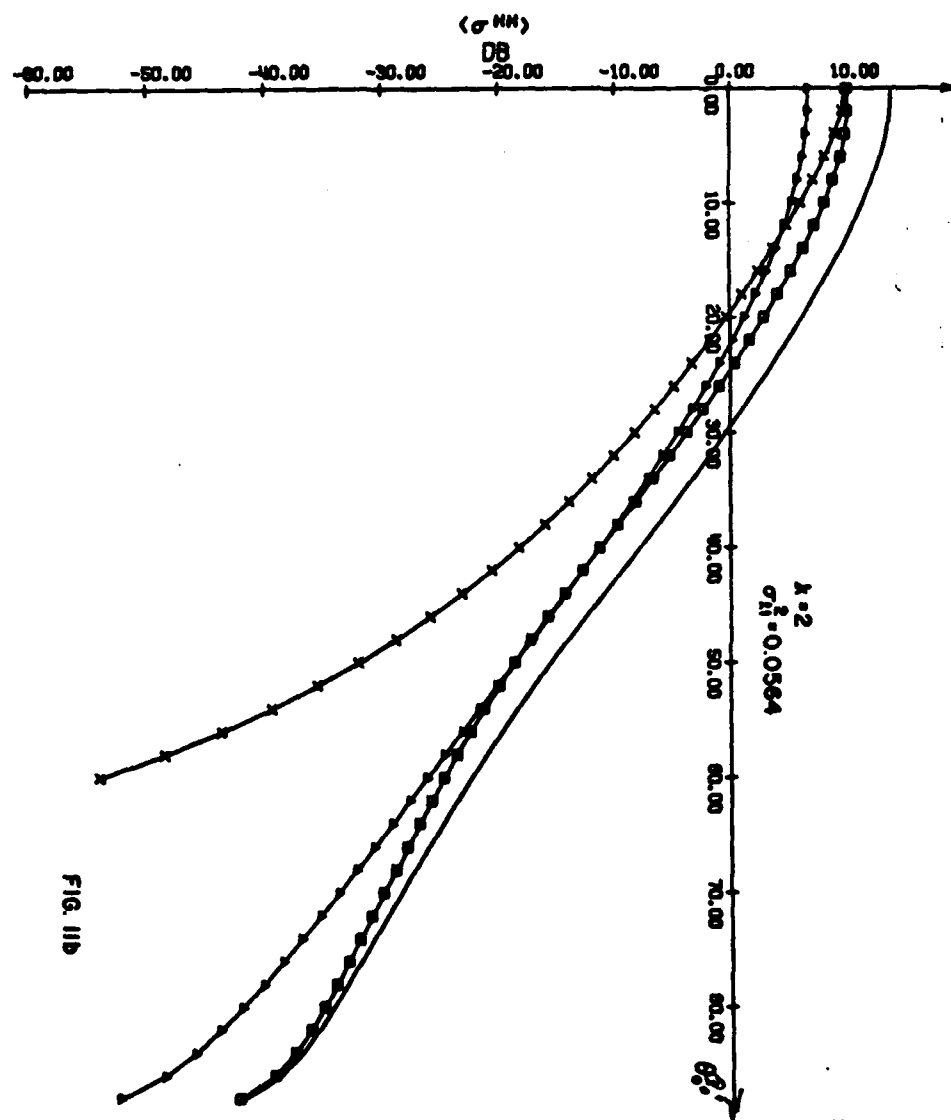


FIG. IIb

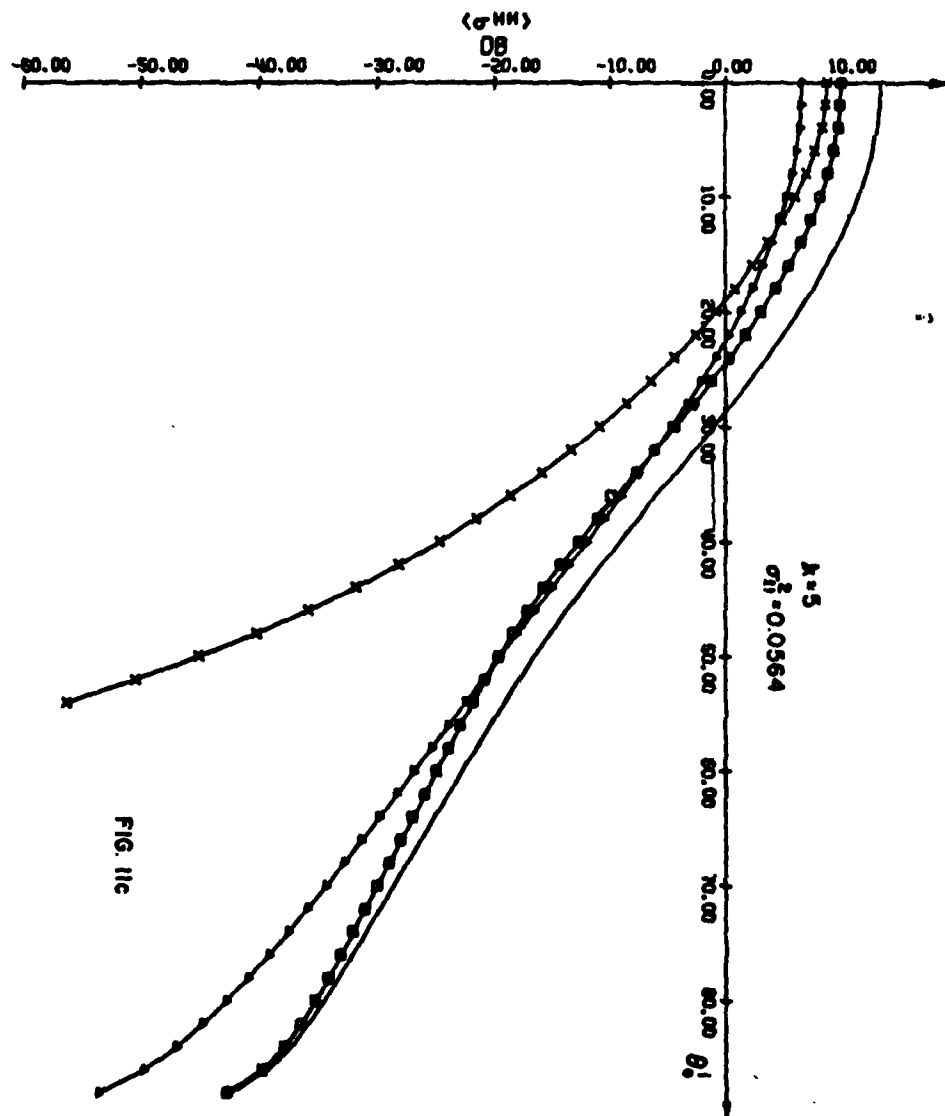
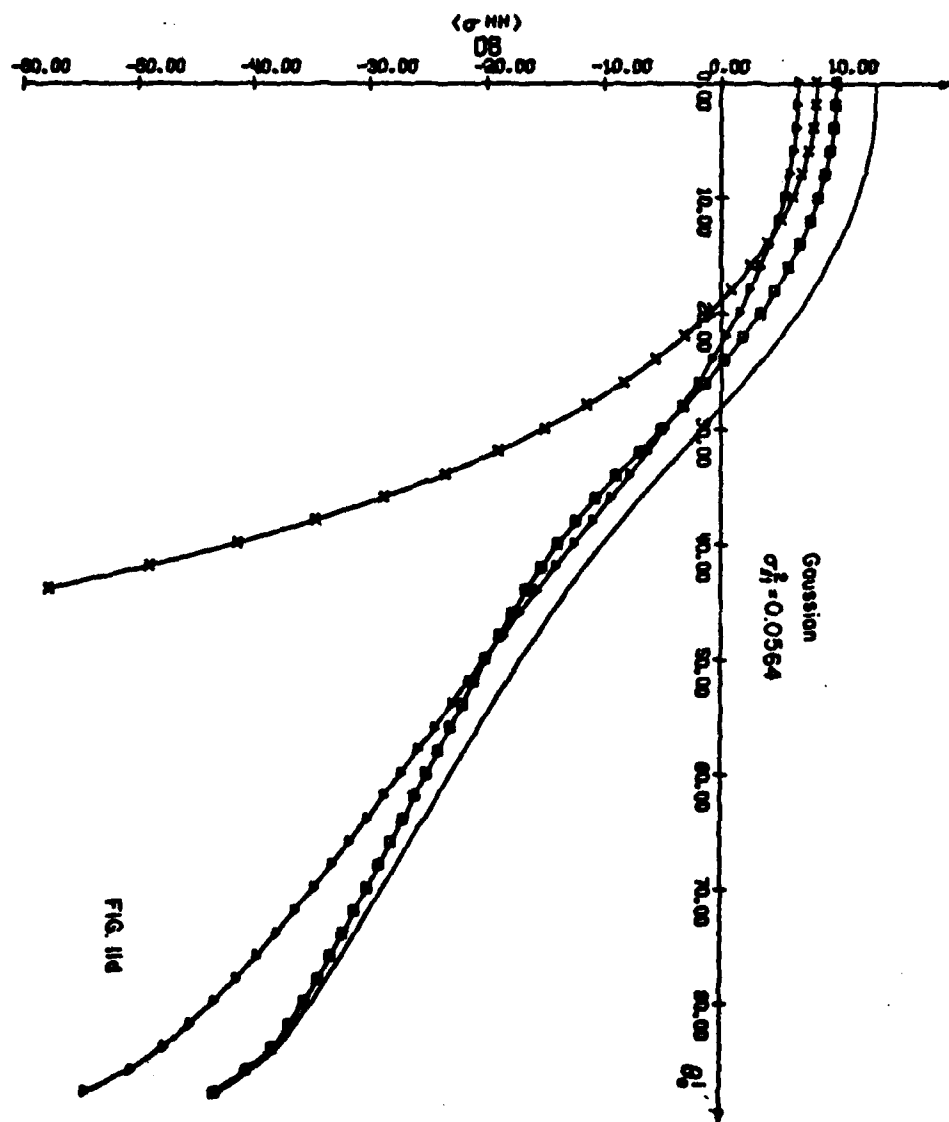


FIG. 11c



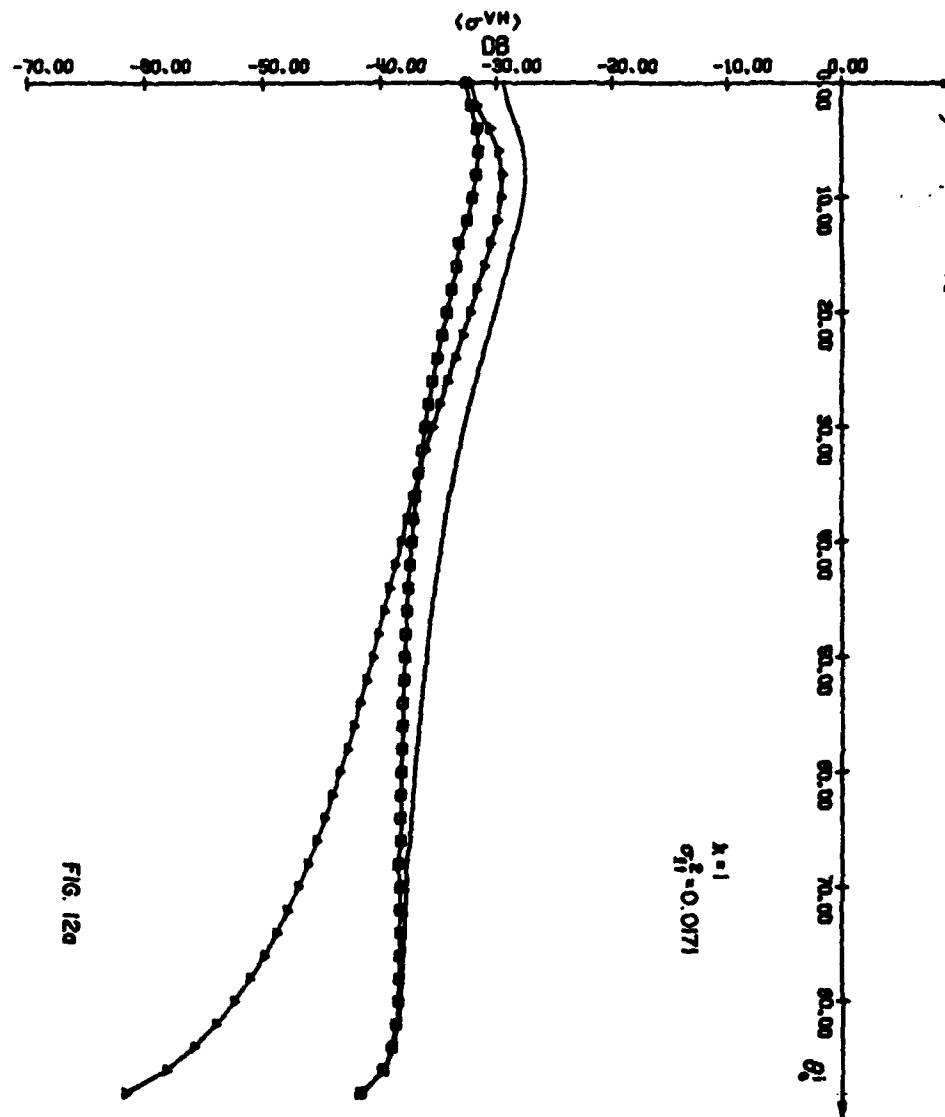


FIG. 12a

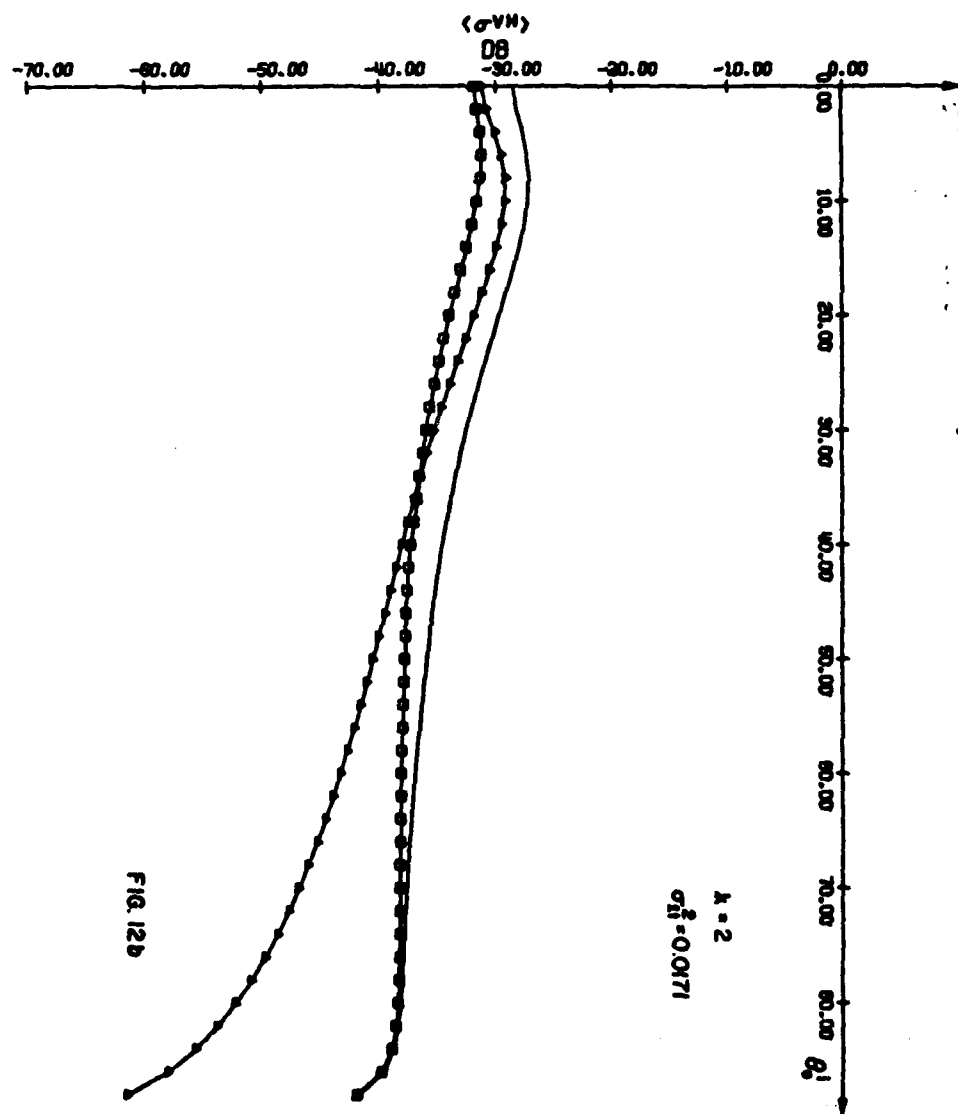


FIG. 12b



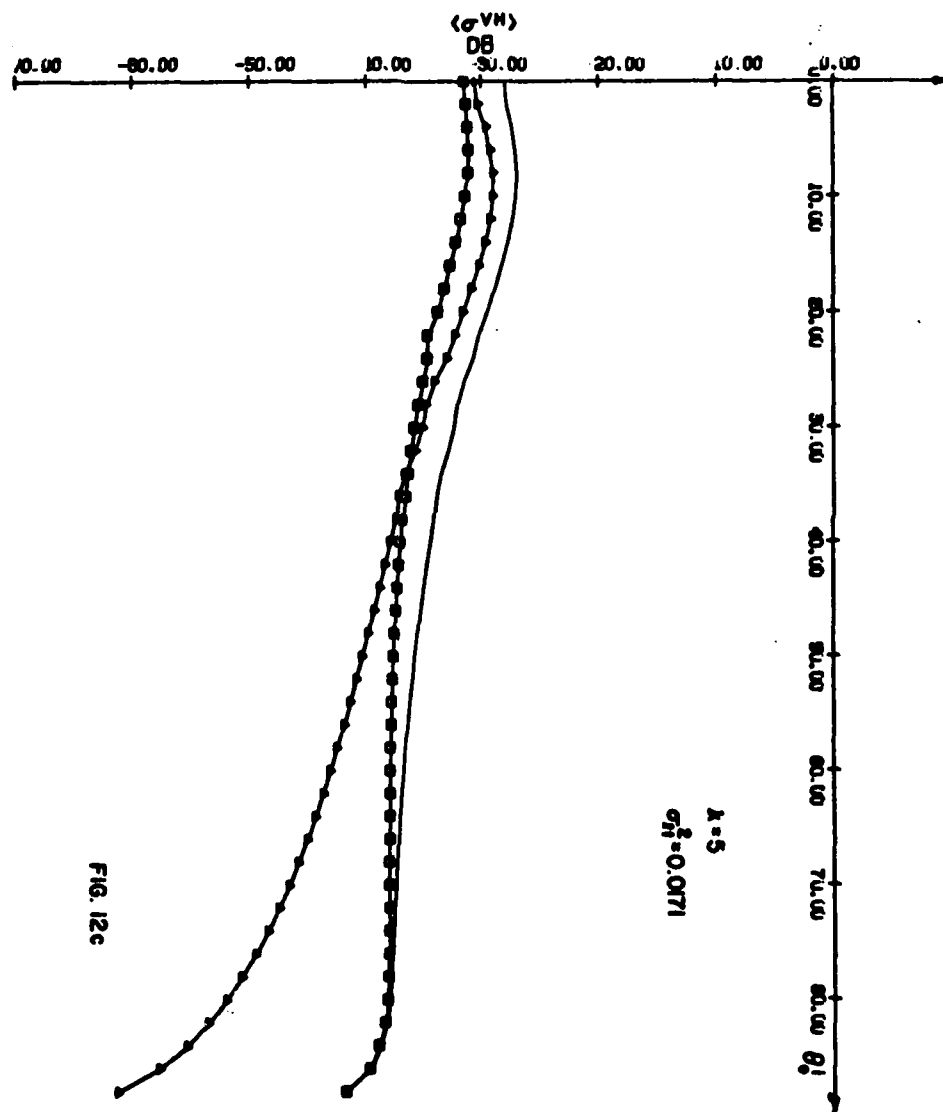
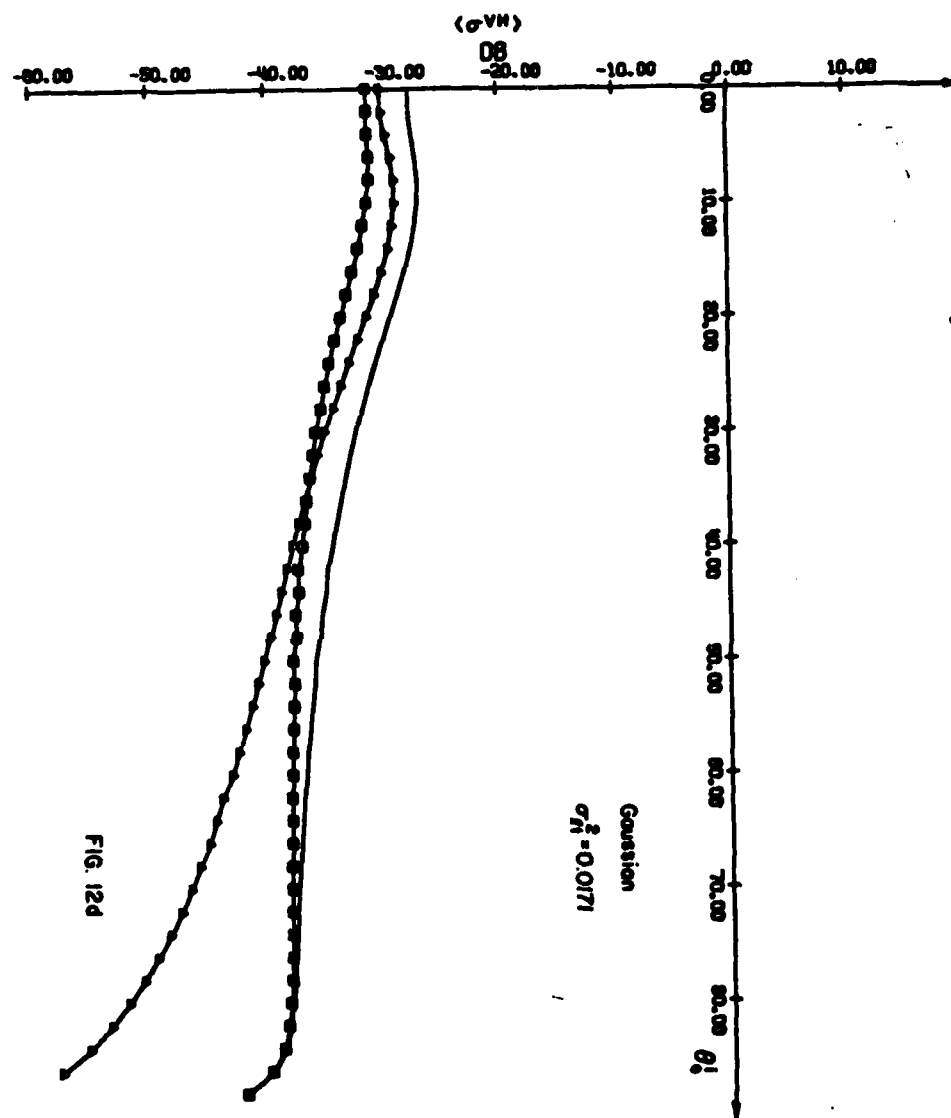


FIG. 12c



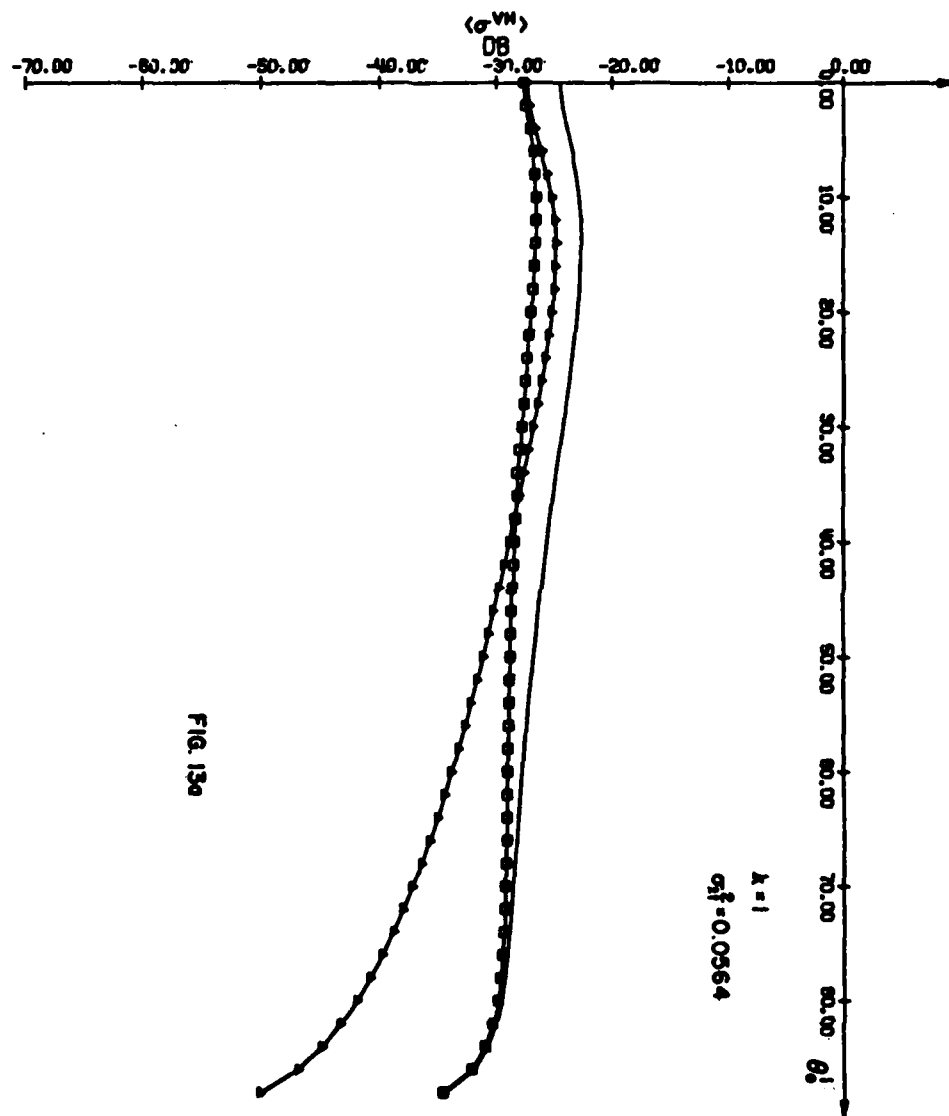


FIG. 13a

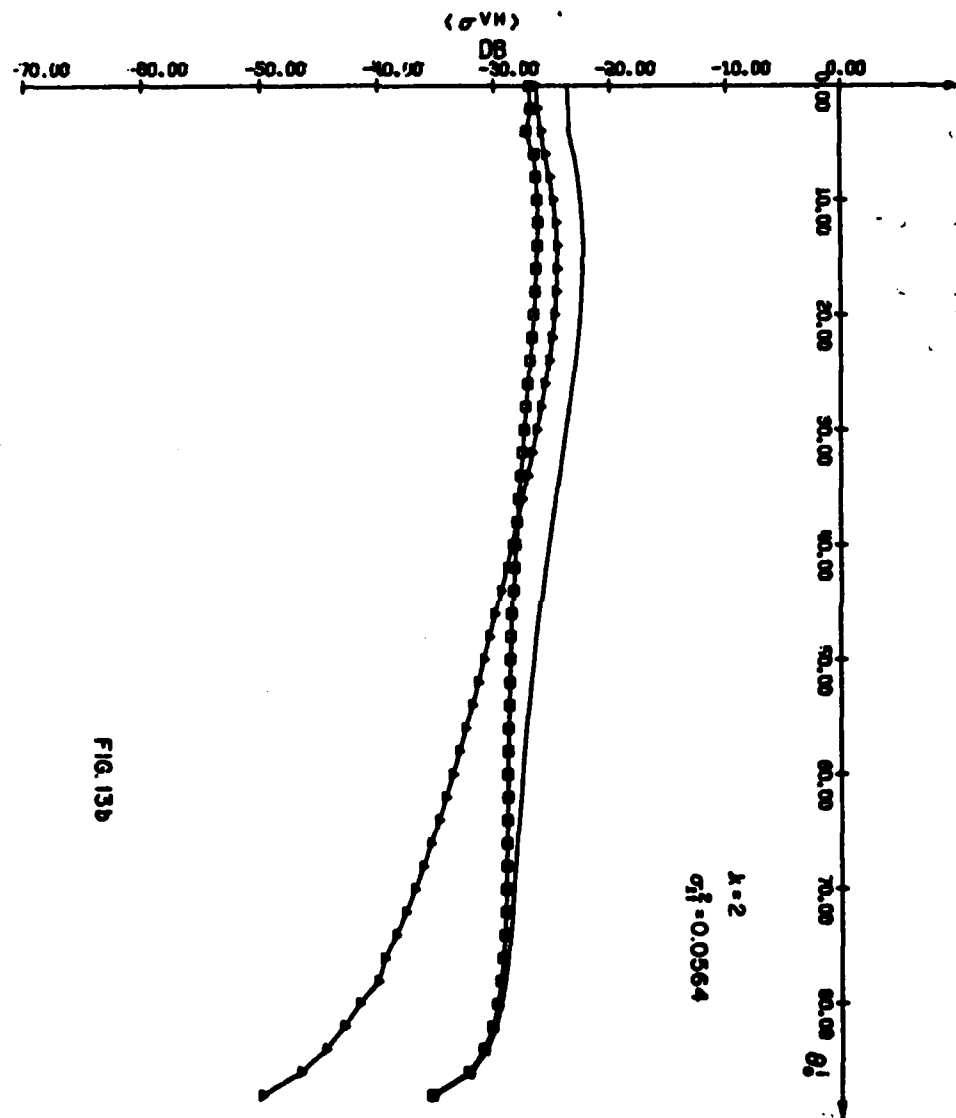


FIG. 13b

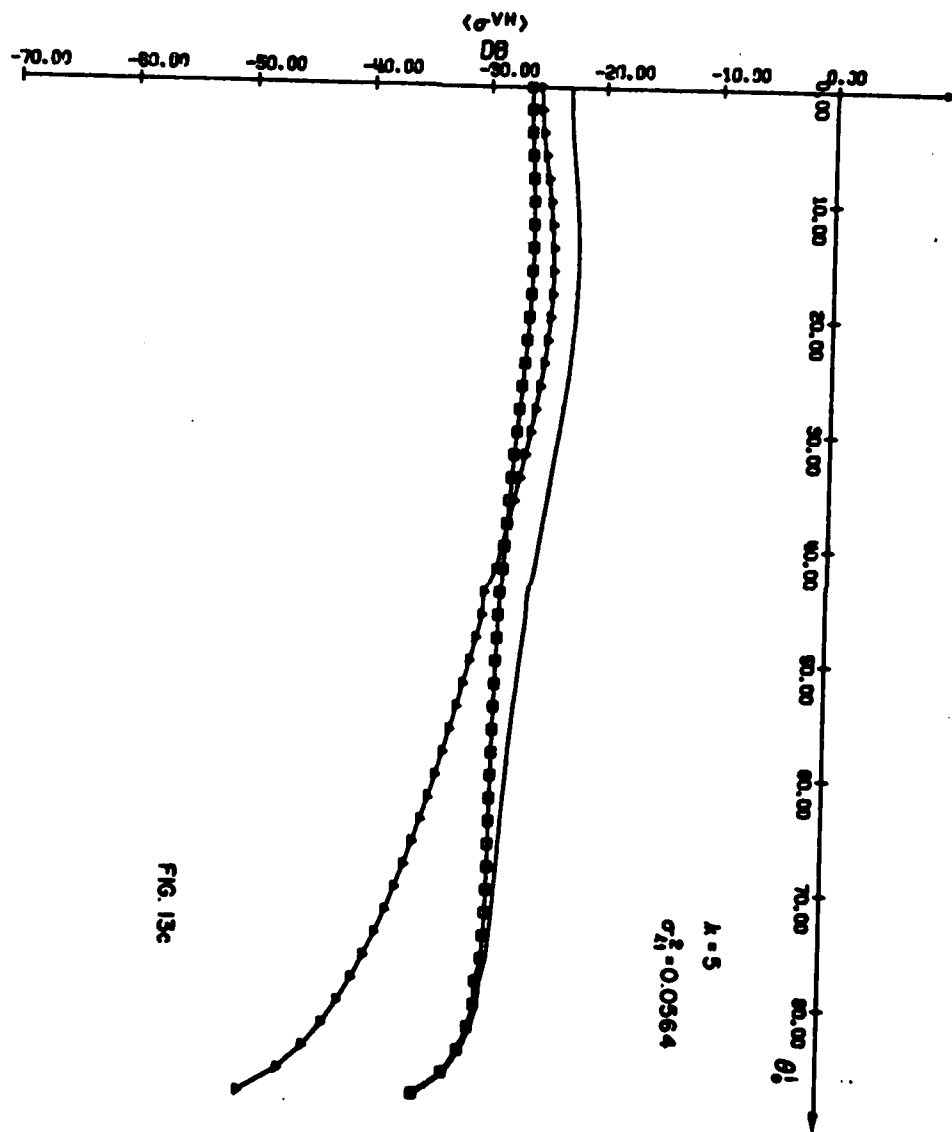


FIG. 13c

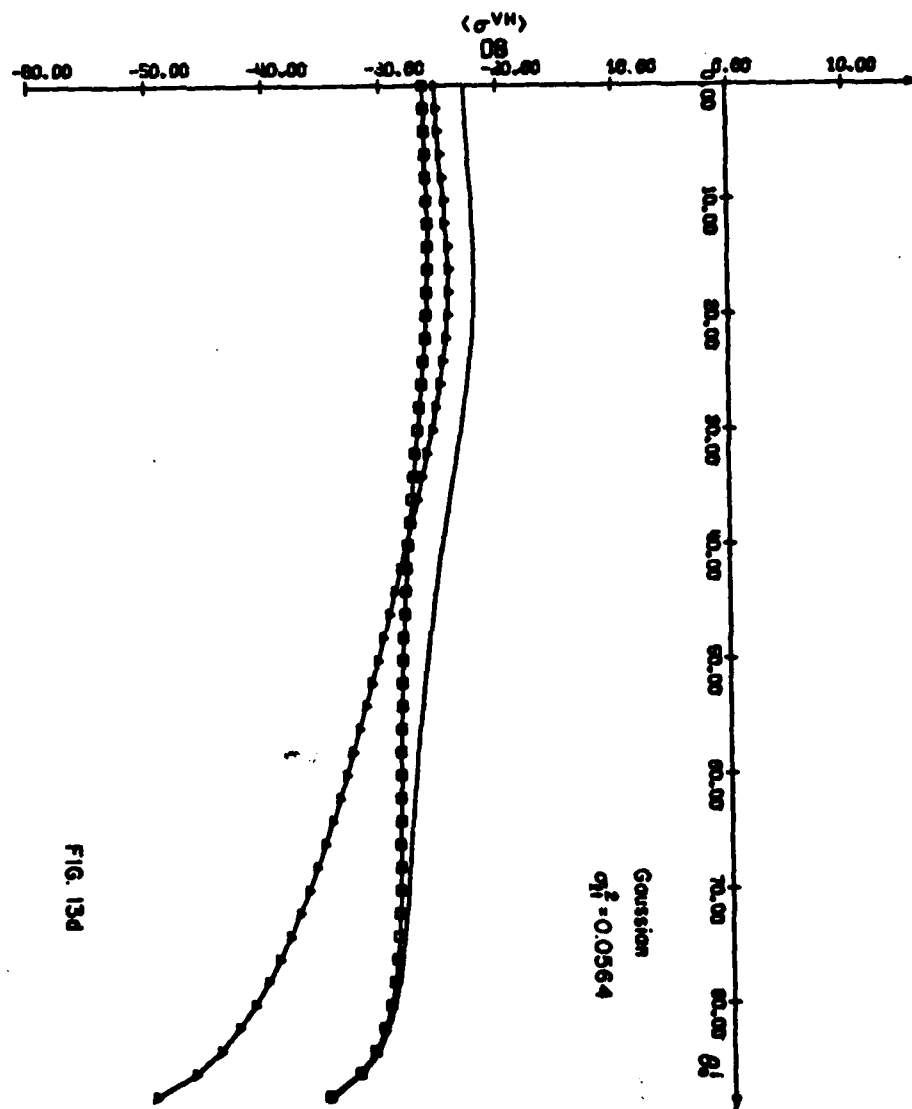


FIG. 13d

